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PRELIMINARY INVESTIGATIONS UPON TWO CELLULOSIC WASTES AS SOURCES FOR XYLOSE

By W. L. Hall, C. S. Slater, and S. F. Acree

ABSTRACT

Technical methods to isolate and utilize the sugars, lignins, and celluloses in cellulosic wastes were begun with a preliminary investigation of peanut hulls and cottonseed-hull bran. The ash content of these materials was extensively studied and the ash was found to be bound in such a manner that with a mild chemical treatment it could be removed almost completely when the materials were subsequently washed with water. Cottonseed-hull bran proved to be an excellent source for the commercial production of the pentose sugar, xylose. An improved method to produce xylose was developed. The process is now being run experimentally on a semicommercial scale so as to obtain xylose in 100-pound-per-day batches.

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I. INTRODUCTION

Cellulose waste products, such as oat hulls, corncobs, and stalks, peanut hulls, cotton burrs, and cottonseed hulls, straws and bagasse, all total annually many million tons. Although a small percentage of these materials is being utilized, the chemist and engineer have an intricate problem to solve before they develop markets and processes for the consumption of the enormous tonnage of such wastes.

The aim of the industrial chemist is to use all of his raw material and have no waste. But when straw or wood is converted into pulp or cellulose fiber, the sugar and lignin are burned to recover admixed chemicals or turned into a stream or cesspool. When hardwood is distilled, or softwood dry cooked with acids to produce fermentable sugars, the cellulose is rendered of no value as such. The ideal to be reached is then to subject the cellulosic wastes to a series of mild extractions to recover and use the products of hydrolysis, such as pectin and arabinose in the case of beet wastes[1] from the sugar-beet industry, and xylose in the case of bagasse[2] or other agricultural wastes. Gums, arabans, xylans, hemicelluloses, lignin bodies—and ash, in those cases where it has a fertilizing value—may also be extracted and used while leaving the plant fibers uninjured, freed of these encrusting or cementing and chemically bound materials, and, hence, more suit-

[1] Z. Angew. Chem., **40**, p. 1305; 1927.
[2] J. Am. Chem. Soc., **26**, p. 1221; 1904.

able for the manufacture of crude fiber commodities or high-grade cellulose.

In this paper are set forth some of the preliminary analyses and work done on the hydrolysis of peanut hulls and cottonseed-hull bran, chiefly to devise methods for production of xylose and xylose molasses without materially injuring the plant fiber for use by the cellulose technologist. These raw materials are available in tonnage lots at central plants. It has been estimated that the peanut industry could readily collect annually 50,000 tons of hulls, and the cottonseed-oil plants can furnish yearly over 1,000,000 tons of cottonseed-hull bran. This bran is obtained as follows:

The cottonseed is mechanically denuded of its useful, adhering fuzz, then broken, and its valuable kernel is removed; or the cottonseed may first be broken, when the kernel and next the fuzz are removed; in either case there is left a fairly clean hull. It is this hull which, when ground, is known as cottonseed-hull bran and has proved to be an excellent source for xylose.

Xylose is a pentose, a 5-carbon aldose sugar ($C_5H_{10}O_5$) discovered by Koch (1886)[3] and further studied by others.[4] It has a wide distribution in many plants. Such agricultural waste products as cottonseed-hull bran, peanut hulls, cornstalks and cobs, cereal straws and hulls, bagasse, etc., are relatively fertile sources for xylose. Woods, and especially hardwoods, contain appreciable quantities; in fact, because it was first obtained from these products it was given the name of "wood sugar."

This sugar is so important as a constituent of plants that all routine analyses include it along with the crude fiber, protein, fats, and ash. It is safe to say that many thousands of analyses have been made for the xylose ($C_5H_{10}O_5$) or pentosan ($C_5H_8O_4)_n$ contents of industrial vegetable materials. However, with all this interest in pentosans of which xylose is probably the chief constituent, no simple methods have been developed heretofore for its commercial production and utilization. That goal is the object of our investigations. Xylose is not known to occur in the free state as does sucrose in beets, cane, and fruits. It is found sometimes as a constituent of gums or starchy materials which can be separated from the cellulose fiber and, perhaps, is also present as an integral part of the cellulose itself. The literature on the chemistry of xylose and its occurrence is quite extensive, a discussion of which is beyond the scope of this paper. From a careful study of the same, however, one may conclude that the xylose molecules must be attached through the aldehyde or alcohol groups or both to a number of different constituents with varying degrees of stability or resistance to hydrolytic separation. With this idea in mind, it has been the aim to liberate or produce the xylose molecule through a combination of physical and chemical treatments and in such quantities as to make xylose a commercial product.

That peanut hulls and cottonseed-hull bran yield xylose on acid hydrolysis is not new to science, but little has been accomplished in the direction of commercial utilization of such wastes. Neither has a detailed study been made as to the best and simplest methods to produce xylose in quantities large enough to open up avenues for its commercial utilization.

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[3] Pharm. Zeit. f. Russland **25**, p. 619; 1886.
[4] Sugar, **25**, p. 124; 1923, gives a good bibliography and discussion.

II. INVESTIGATIONS TO DETERMINE SUITABLE CONDITIONS FOR XYLOSE PRODUCTION

1. MOISTURE CONTENT

The percentage of moisture in air-dried cellulosic materials varies with the temperature and humidity of the surrounding atmosphere. It is important to determine this moisture content in order to know the actual weight of dry substance bought and used in manufacturing processes and the percentage yields obtained. It is also important to know the moisture content in the analysis of cellulosic materials in order to evaluate correctly the other constituents. Results of analyses are often given on the original air-dried material and on the "bone-dry" or "oven-dried" substance supposed to be free of absorbed water.

The moisture content of peanut hulls as recorded in the literature[5 6 7], varies with samples. Those samples used in this investigation also gave varying values according to the methods used in the determination.

TABLE 1.—*Moisture content of peanut hulls and cottonseed-hull bran*

Material	Dried 10 days at 105° C.	Toluene method [1]	Vacuum desiccation over H_2SO_4
	Per cent	*Per cent*	*Per cent*
Commercial hulls	8.6	9.0	[2] 7.5
Commercial ground hulls	8.5	7.6	6.3
Specially ground air-blown hulls		4.0	4.5
Cottonseed-hull bran		11.8	[3] 12.25

[1] Values were obtained by boiling 100 g samples of the hulls with water-saturated toluene and measuring the volume of water condensed with the toluene in an apparatus similar to the usual water-determination apparatus.
[2] Reed (see footnote 6, below) found an average of 7.9 per cent.
[3] Markley, J. Am. Soc. Agron., **20**, p. 1103; 1928.

2. ASH CONTENT

All who have had experience in the production and crystallization of sugars know the advantages of dealing with sirups or extracts low in ash content. Ash present in appreciable quantities materially interferes with the crystallization of sugars. Since the waste agricultural products studied show relatively high total ash contents, a detailed study of the total bound and removable ash was made. It was found that the total ash was largely made up of two components, namely, adhering dirt and an absorbed or chemically bound ash.

Commercial peanut hulls averaging 5.0 per cent total ash were separated into three fractions by mechanically agitated sieves: First, the fraction which would pass through a No. 20 sieve; second, the fraction which was retained by a No. 20 sieve, but would pass through a No. 8 sieve; and third, the fraction that was retained by a No. 8 sieve. The ash content of each fraction was determined and also the relative distribution of the hulls of these particular sizes. The results are tabulated in Table 2.

[5] Exp. Sta. Record, **3**, pp. 42 and 148; 1891.
[6] Texas Agr. Exp. Sta. Bull. No. 222, p. 10; 1917.
[7] U. S. Dept. Agr. Bull. No. 1096, p. 6; 1922.

TABLE 2.—*Mechanical removal of extraneous ash (dirt) from 100 g samples of peanut hulls by sieving or air blasting*

Treatment	First fraction		Second fraction		Third fraction	
	Weight of hulls on basis of original sample	Ash	Weight of hulls on basis of original sample	Ash	Weight of hulls on basis of original sample	Ash
Mechanical shaking:	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
½ minute	11.5	33.9	10.2		78.3	2.5
1 minute	12.5		9.5		78.0	2.4
2 minutes	12.5	31.3	9.0	4.9	78.5	2.3
5 minutes						2.0
Blasted with air for 3 minutes from a 30-pound air-pressure line						1.9

Most of the ash was separated with that fraction which passed through the No. 20 sieve. Over 30 per cent of that fraction was ash. The hulls retained by the No. 8 sieve contained only 2.0 to 2.5 per cent ash. Vigorous air blowing of a sample in a No. 8 sieve also removed the adhering dirt so that the sample contained less than 2.0 per cent of ash. The residual or bound ash in hulls of the third fraction resisted leaching with hot water. An acid extraction of the dirt-free hulls removed this remaining ash down to 0.15 to 0.4 per cent and left a very pure organic fiber for the manufacture of xylose and cellulose.

The nature of this residual or bound ash is of both theoretical and practical importance. It may consist of phosphates, silicates, etc., insoluble in water but soluble in acids, or of metallic cations like potassium, sodium, calcium, etc., combined with fairly strong acid groups making up the complex cellulosic matter, or of both types. When the cleaned hulls were burned, the ash residue was decidedly alkaline to usual indicators. It was titrated with acid, using brom-cresol green indicator, and as the end points developed slowly, the mixture was allowed to stand between additions of acid. Warming and then cooling the sample during the titration accelerated the procedure. The titration value indicated that the ash was largely a carbonate instead of a phosphate, silicate, etc. Those papers in the literature that deal with detailed analyses of the ash content of peanut hulls [8] are in agreement with the data showing large amounts of basic constituents especially potash in comparison with the acid constituents, such as phosphates, etc.

If the greater part of the potash present were combined with acid-like groups of the plant material, or absorbed thereupon, potassium carbonate should be formed by ashing, and was actually found. Furthermore, combined ash of such a nature, upon treatment with mineral acids, would form the inorganic salt of the mineral acid which could then be washed out.

In this leaching with the dilute mineral acid, the alkali-combining power of the peanut hull, or possibly the carboxyl content, was not appreciably altered in the majority of cases; for additional treatments

[8] See footnotes 5, 6, and 7, p. 331.

of the ash-free hulls with alkali, and subsequent washing, produced hulls having again a high ash content which in turn could again be removed by the acid treatment, but not with hot water. The failure of hot water to remove the alkali metal shows that it was not present as the easily hydrolyzed salt of a lignin phenolic group, but possibly as the salt of a carboxylic or stronger acid.

In harmony with this idea is the fact that such relatively ash-free hulls when finely ground may be titrated rapidly, at first, against alkali and phenolphthalein. Cleaned hulls treated with an excess of sodium hydroxide were washed until neutral, dried, and ashed; nearly pure sodium carbonate was formed as shown by analysis.[9]

The following table presents experimental evidence that such an ash-combining power was present.

TABLE 3.—*Effect of hydrolysis on the ash content of peanut hulls. Hull residues oven dried at 105° C.*

Character of hulls	Treatment	Ash remaining in thoroughly washed hulls	Titration of ash ml 1.0 N H_2SO_4 per gram of ash
		Per cent	
Commercial hulls	None	[1] 5.0	8.3
Do	Mechanically cleaned, air blown	[1] 1.9	11.
Commercial hulls mechanically cleaned	0.18 N NaOH for 1 hour at 100° C	2.0	14.
Do	0.50 N NaOH for 1 hour at 100° C	2.3	17.
Do	0.16 N HNO_3 for 1¼ hours at 100° C	.18	4.8
Do	0.29 N HCl for 1 hour at 100° C	.40	.72
Commercial hulls mechanically cleaned	0.25 N NaOH two separate hydrolyses 1½ hours each at 100° C.	1.7	17.
Commercial hulls mechanically cleaned, hydrolyzed 1½ hours at 100° C. (twice) with 0.25 N NaOH.	0.32 N HNO_3 1 hour at 100° C	.16	.2
Commercial hulls mechanically cleaned	0.32 N HNO_3 2 hours at 100° C	.18	.04
Commercial hulls mechanically cleaned, hydrolyzed 2 hours at 100° C. with 0.32 N HNO_3.	0.25 N NaOH 1 hour at 100° C	3.04	18.
Commercial hulls (uncleaned)	0.11 N HNO_3 old battery hydrolysates fortified with acid.	[2] 3.08	----------
Commercial hulls (uncleaned) extracted in battery with 0.11 N HNO_3.	1.0 N NaOH 1½ hours; 10 pounds steam pressure.	3.53	----------

[1] Hulls not washed.

[2] The high ash was due to the presence of an accumulation of inorganic materials in the battery hydrolysates which were run at 10 pounds steam pressure in a regular battery process described later in this paper.

Similar experiments with cottonseed-hull bran lead to the same conclusions regarding the acid groups and ash, as shown in Table 4. Naturally, cottonseed hulls have less chance than peanut hulls to contain adhered dirt.

[9] The ash titrations shown in column 4 of Tables 3 and 4 should be compared with 18.86 ml N H_2SO_4 required per gram of sodium carbonate and 14.50 ml N H_2SO_4 per gram of potassium carbonate.

TABLE 4.—*Effect of hydrolysis on the ash content of cottonseed-hull bran. Bran residues oven dried at 105° C.*

Character of bran	Hydrolysis treatment	Ash remaining in thoroughly washed bran	Titration ml 1.0 N H_2SO_4 per gram of ash
		Per cent	
Commercial cottonseed-hull bran	None	[1] 2.3	14.
Do	Distilled water 7 hours on the steam bath	1.8	15.5
Do	Completely covered with 0.16 N HNO_3 at room temperature for 24 hours.	.54	----------
Do	Completely covered with 0.16 N H_2SO_4 at room temperature for 24 hours.	.47	----------
Do	0.11 N HCl for 1 hour at 100° C	.46	11.0
Commercial cottonseed-hull bran hydrolyzed once, 1 hour with 0.11 N HCl at 100° C.	do	.46	3.9
Commercial cottonseed-hull bran hydrolyzed twice, 1 hour each with 0.11 N HCl at 100° C.	0.26 N HCl for 1½ hours at 100° C	.46	.21
Commercial cottonseed-hull bran	0.26 N HCl for 1½ hours at 25° C	.20	<0.1
Do	do	.20	.7
Do	0.26 N HCl for 3 hours at 25° C	.16	1.8
Do	0.26 N HCl 2 separate hydrolyses 1 hour each at 100 C.	.12	3.5
Do	0.12 N HNO_3 for 1 hour at 100° C	.52	10
Commercial cottonseed-hull bran hydrolyzed twice with 0.11 N HCl at 100° C.	0.17 N NaOH for 1 hour at 100° C	2.4	17
Commercial cottonseed-hull bran	do	2.6	13
Commercial cottonseed-hull bran hydrolyzed once 0.26 N HCl at 100° C.	0.17 N NaOH 2 separate hydrolyses 1 hour each at 100° C.	2.8	16

[1] Bran not washed.

3. XYLOSE CONTENT

In the production of xylose from agricultural wastes, one is handicapped by the lack of simple, precise analytical methods for its exact estimation. It has long been known that pentoses, upon distillation in a 12 per cent hydrochloric acid solution, are converted almost quantitatively into furfural.[10] The resulting furfural which is contained in the distillate can be determined gravimetrically with phloroglucine[11] or thiobarbituric acid[12] or volumetrically.[13] Waste materials containing xylose, and xylose extracts from the same, may also contain other organic compounds—that is, arabinose, glucuronic acid, etc.—in lesser quantities, which likewise yield furfural upon distillation with 12 per cent hydrochloric acid. Difficulties were encountered in quantitative furfural determinations if the acid distillation was made upon material containing nitric acid or nitrates. Calculations of xylose yields and xylose contents, based upon furfural determinations, are only approximate and indicative.[14]

(a) PEANUT HULLS

The nature of the work so far on peanut hulls has been only preliminary. Hydrolyses were made upon commercial peanut hulls with the hope of determining the amount of pentoses present and the easiest methods of extracting such from the hulls to produce the

[10] Official and Tentative Methods of Analysis. 2d Edition, 1925. Association of Official Agricultural Chemists, Box 290, Pennsylvania Avenue post office, Washington, D. C

[11] See footnote 10.

[12] Dox and Plaisance, J. Am. Chem. Soc., **38**, p. 2156; 1916.

[13] Pervier and Gortner, J. Ind. Eng. Chem., **15**, pp. 1167 and 1255; 1923.

[14] The method of Dox and Plaisance (footnote 12) was used exclusively for furfural determinations. The furfural value times the factor, $\frac{C_5H_{10}O_5}{C_5H_4O_4}=1.563$, was used for pentose or xylose equivalent in all such calculations in this paper.

sugars, chiefly xylose. Furfural determinations were made upon untreated peanut hulls, and the calculated furfural yields were compared with those obtained from hull residues after they had been hydrolyzed in various ways. This comparison gave an insight into the efficacy of the hydrolysis treatment in removing furfural-yielding compounds.

TABLE 5.—*Furfural yields of unhydrolyzed and hydrolyzed peanut hulls*

Sample	Treatment	Furfural yield oven-dried basis	Pentose equivalent based on furfural determination
		Per cent	*Per cent*
Commercial hulls	None	10.9	17.0
Do	Commercially ground	10.8	16.9
Do	Mechanically cleaned, then finely ground	13.0	20.3
Do	Hulls hydrolyzed 1 hour at 100° C. with 2 per c. cent NaOH, washed and analyzed.	11.1	17.3
Do	Hulls hydrolyzed with 0.15 *N* HNO_3 in a battery run, washed and analyzed.	6.5	10.1
Do	Hulls hydrolyzed with 0.2 *N* H_2SO_4 in a battery run, washed and analyzed.	5.1	7.9
Commercially ground hulls.	Hulls[1] hydrolyzed with cold 42 per cent HCl, washed and analyzed.	<1.0	<1.5

[1] Such an acid treatment disintegrated and charred the hulls, leaving them worthless for further use as cellulose sources.

Table 5 gives a few representative analyses showing that peanut hulls may contain from 17 to 20 per cent of furfural-yielding materials, the major portion of which must have been derived from pentoses. The yields of furfural from these hydrolyzed hulls were materially diminished by the hydrolyses. This fact indicated that pentoses were being removed from the fiber mass.

A very concentrated acid, like 42 per cent hydrochloric acid, removed almost completely in the cold the furfural-yielding materials.

A battery cycle method of three successive hydrolyses was then started to obtain sugar on a small scale by a method similar to commercial battery extractions. In this system the fresh hulls were extracted with the concentrated sugar solution containing the hydrolytic agent, while the final treatment, for twice extracted hulls, was with the most dilute sugar solution containing the hydrolytic agent. These steps were continued in the conventional cycle until the hulls were finally washed with water to recover adhering materials, then removed from the cell for other uses, such as production of cellulose fibers. This cell was then filled with fresh hulls for the next cycle, etc.

Table 6 gives data on different batteries, Nos. 18 to 65, which are sufficiently representative of these runs. In these and subsequent cases the Brix readings (per cent solids by weight for sucrose solutions) are used only in an indicative sense for possible concentrations of xylose. As the hulls used for these runs were neither physically nor chemically cleaned, the dissolved ash was one source of error in these readings.

TABLE 6.—*Battery extractions of peanut hulls*

	Experiment number	Weight of air dried commercial hulls	Weight of air-dried hulls after hydrolysis	Brix of final hydrolysates
Hydrolyzed with approximately 4 liters of 0.2 *N* H_2SO_4 at 10 pounds steam pressure for 1 hour.	18	350	229	10.3
	19	350	228	9.0
	20	350	222	10.5
	21	350	222	8.9
	22	350	206	8.9
	23	350	218	9.0
	24	350	204	8.1
	25	350	202	7.6
	26	350	204	7.6
	27	350	199	8.7
	28	350	195	8.0
	29	350	199	8.0
	30	350	212	9.2
	31	350	210	9.5
	32	350	211	9.6
	33	350	182	10.0
	34	350	209	9.7
	35	350	238	9.7
	36	350	216	10.0
	37	350	184	9.7
	38	350	197	10.0
	39	350	202	9.8
	40	350	200	11.0
	41	350	209	10.5
	42	350	196	10.5
	43	350	206	10.7
	44	350	239	10.6
	45	350	253	10.8
Average		350	210	9.5
Hydrolyzed with approximately 8 liters of 0.16 *N* HNO_3 at 10 pounds steam pressure for 1 hour.	50	1,200	740	5.0
	51	1,000	695	6.5
	52	1,000	670	6.5
	53	1,000	695	6.5
	54	1,000	650	6.0
	55	1,000	670	5.0
	56	1,000	630	7.0
Average		1,029	678	6.1
Hydrolyzed with approximately 8 liters of 0.35 *N* HNO_3 at 10 pounds steam pressure for 1 hour.	61	1,000	670	6.5
	62	1,000	660	5.0
	63	1,000	650	6.0
	64	1,000	----------	5.5
	65	1,000	----------	5.0
Average		1,000	660	5.6

It is to be noted that in the case of nitric acid a doubling of the acid strength had little effect upon the concentration of the extract, also that sulphuric acid gave proportionally higher concentrations. Just whether the increment was due to increased sugar yields will require a more detailed study. The residual hulls were generally light in color and had lost by extraction about 34 to 40 per cent of their weight. The extracts showed by titration a small amount of organic acids. Attempts to isolate crystalline xylose from these hydrolysates were rather discouraging and require further study.

(b) COTTONSEED-HULL BRAN

Our investigations upon cottonseed-hull bran have been more extensive, since the bran has greater possibilities as a source for

xylose. The researches of Euler,[15] Hudson and Harding,[16] Sherrard and Blanco,[17] and just recently Markley [18] in this laboratory, furnish fundamental and valuable information in this field. Markley found that such bran contained sufficient xylanlike bodies to give 22.29 per cent of its air-dried weight as furfural when distilled with 12 per cent hydrochloric acid, and that a 22.2 per cent furfural yield corresponded to 43.2 per cent pentose on the basis of Kröber's formulæ.[19] Just what was the complete source of the furfural is not definitely known. However, other experiments indicated that the greater part came from pentosans. A series of hydrolysis experiments were made upon the bran in order to ascertain the most favorable conditions for hydrolysis. The results are tabulated in Tables 7 and 8.

TABLE 7.—*Hydrolysis of cottonseed-hull bran with dilute hydrochloric acid—100 g samples treated with 300 ml of acid*

Experiment No.	Character of bran	Hydrolysis treatment	Furfural determination on hydrolysate—percentage on basis of original weight of bran	Pentose equivalent	Furfural determination on bran after hydrolysis—bran washed dried at 100° C.	Pentose equivalent
			Per cent	*Per cent*	*Per cent*	*Per cent*
1	Commercial cottonseed-hull bran.	0.26 *N* acid, 1½ hours at 25° C.	<1.0	<1.0	25.3	39.5
2	do	0.26 *N* acid, 3 hours at 25° C.	<1.0	<1.0	25.3	39.5
3	do	0.11 *N* acid, 1 hour at 100° C.	1.96	3.05	----------	----------
4	Bran from experiment No. 3 thoroughly washed.	0.11 *N* acid, 1 hour at 100° C.	5.77	9.02	18.5	28.9
5	Bran from experiment No. 4 thoroughly washed.	0.26 *N* acid, 1½ hours at 100° C.	8.18	12.8	10.7	16.7
6	Commercial cottonseed-hull bran.	0.26 *N* acid, 1½ hours at 100° C.	14.8	23.3	12.1	18.9

That cold dilute acid does not split off appreciable amounts of xylose or furfural-yielding compounds was quite interesting. When a given lot of bran was hydrolyzed by successive treatments with hydrochloric acid at 100° C., the furfural or xylose yield was successively increased in a step-wise manner. The sum of the furfural so obtained plus that which the treated bran yielded on analysis was in fair agreement with the amount originally determined.

The function of time in relation to the amount of sugar produced by hydrolysis of the bran with 2.5 per cent (0.7 *N*) hydrochloric acid was studied. Individual 8 g samples were refluxed on an electric hot plate with 400 ml of acid for definite time intervals, ranging from 5 minutes to 2.5 hours. The aldose sugars produced during each interval were determined by an iodine and alkali titration procedure that is being developed in conjunction with this problem. The results are given in Table 8.

[15] Euler, H., Grundlagen und Ergebnisse der Pflanzenchemie I, Braunschweig, p. 44; 1908.
[16] J. Am. Chem. Soc., **39**, p. 1038; 1917.
[17] J. Ind. Eng. Chem., **12**, p. 1160; 1920.
[18] See footnote 3 to Table 1, p. 331.
[19] See footnote 10, p. 334.

TABLE 8.—*Hydrolysis of cottonseed-hull bran (air dried) with 2.5 per cent hydrochloric acid at 100° C.*

	Time (in minutes)									
	5	10	15	20	25	30	60	90	120	150
Per cent xylose equivalent in hydrolysate, on basis of bran used—iodine titration	19.8	27.0	27.9	29.9	31.0	36.9	37.6	37.3	36.5	36.8
Per cent xylose equivalent in hydrolysate, on basis of bran used—alkali titration	18.2	24.5	25.9	27.9	29.1	34.5	35.7	35.0	34.3	35.0

It is seen from Table 8 that about one-half of the total sugar was formed in the first five minutes, and thereafter the percentage mounts gradually to a maximum in one hour. This maximum value, 37.6 per cent xylose, approximates the calculated pentose content, based on total furfural determinations given in Table 8, and when corrected for bran moisture gives the equivalent xylose yield on the basis of oven-dried bran; namely, 42.7 per cent. Markley [20] found that cottonseed-hull bran yielded, on an oven-dried basis, under a similar treatment an equivalent of 43.5 per cent xylose. He based his value for xylose upon a copper value for reducing sugars but made only a final determination after hydrolysis for 2.5 hours.

Experiments were next made upon larger quantities of bran. The bran, 2,000 g, was given a preliminary acid wash with enough 0.16 *N* cold nitric acid to cover it completely. Between 4 and 5 liters were required. After soaking for 15 hours the bran was drained and washed, then treated with sufficient dilute acid to make the total volume of acid present about 6 liters of the desired normality. The batch was then first heated for one-half hour by escaping steam in an autoclave to 80° C. and finally cooked at 10 pounds steam pressure. Results are given in Table 9.

TABLE 9.—*Pressure hydrolysis of cleaned cottonseed-hull bran*

2,000 g bran hydrolyzed with 6 liters acid at 10 pounds steam pressure	Brix	Sugar in hydrolysate determined by titration with iodine and alkali	Sugar yield, on basis of bran used
		Per cent	*Per cent*
0.16 *N* HNO_3 for 1 hour	7.0		
0.16 *N* HNO_3 for 2 hours	11.5	8.8	26
0.08 *N* H_2SO_4 for 2 hours	5.9		
0.16 *N* H_2SO_4 for 2 hours	10.0	6.7	20
0.32 *N* H_2SO_4 for 2 hours	9.0	7.0	21

By way of comparison a batch of bran (2,000 g) was hydrolyzed as above with 0.16 *N* nitric acid, except that the preliminary ash treatment was omitted. A Brix reading of 9.0 resulted, yet the sugar content was only 2 per cent. Here the greater part of the hydrolyzing acid was neutralized by the alkali salts in the bran, and, consequently,

[20] See footnote 3 to Table 1, p. 331.

was not available for hydrolytic activity. However, when the extract, which was quite colloidal and gummy, was further fortified with nitric acid to 0.16 *N* and again pressure cooked, the sugar content increased to 6.5 per cent. This evidence bears out the well-known fact that xylans are easily split off by dilute acids under pressure and that a higher concentration of acid is necessary to complete the hydrolysis. This experiment and those recorded in the table above bring out clearly that insufficient acid concentration and too short hydrolytic periods are to be avoided, and there is no advantage in doubling the concentration of the acid (0.32 *N*). Longer cooking periods were also found to be unnecessary. In all pressure cooks the odor of furfural was quite noticeable, and especially so for the higher acid concentrations. The probability of the furfural being produced from xylose would be greater for the more concentrated acid cooks. Here, again, is another factor favoring hydrolysis with weak acid.

The bran residue (0.16 *N* H_2SO_4, two-hour cook, Table 9) was thoroughly washed and rehydrolyzed as before with 0.16 *N* sulphuric acid. The second hydrolysate had a Brix of only 0.5, showing that the first hydrolysis was sufficient. In contrast to this, the bran residue (0.08 *N* H_2SO_4, two-hour cook, Table 9) when similarly treated with 0.16 *N* sulphuric acid, gave a Brix reading of 3.7, showing that the first hydrolysis in this case was insufficient. These brans were again so hydrolyzed for the third time, producing small Brix values, 1.3 and 1.6, respectively.

Such a process for the complete removal of sugar, even if only one cook were made, would accumulate, on a commercial scale, large volumes of weak sugar solutions. The battery method of three successive hydrolyses was next studied, whereby concentrated extracts were obtained. A detailed study of the efficiency for each extraction is given by the data in Table 10.

TABLE 10.—*Battery extraction of cleaned cottonseed-hull bran: 2,000 g bran hydrolyzed with 6 liters of 0.16 N H_2SO_4 extract, for two hours at 10 pounds steam pressure*

Experiment No.	Brix increments for each extraction			Total Brix	Experiment No.	Brix increments for each extraction			Total Brix
	First	Second	Third			First	Second	Third	
1	7.8	3.2	2.3	13.3	11	6.5	3.3	1.4	11.2
2	8.3	2.0	1.0	11.3	12	5.5	3.1	1.0	9.6
3	6.8	2.7	1.5	11.0	13	6.6	3.0	1.4	11.0
4	7.5	2.2	1.3	11.0	14	6.0	3.0	1.7	10.7
5	7.3	2.2	1.7	11.2	15	5.5	2.0	.9	8.4
6	6.3	2.3	2.3	10.9	16	4.4	1.4	1.5	7.3
7	5.9	4.0	2.5	12.4	17	4.3	3.3	2.3	9.9
8	8.2	2.9	2.0	13.1	18	5.2	3.0	2.2	10.4
9	5.5	3.5	2.8	12.8	19	5.3	3.5	-----	-----
10	6.0	2.8	1.5	10.3	20	6.8	-----	-----	-----
					Average of results	6.3	2.8	1.7	10.9

In each case acid-cleaned bran was used and a Brix reading made upon a portion of the drained hydrolysate before and after the cook. A titration and acid adjustment of the hydrolyzing solution was made so that successive cooks were always approximately 0.16 *N* mineral acid. The end points in the titration were determined by the use of

thymol blue indicator in the acid region and interfering colors present in the solutions were compensated for by comparison. The difference between the initial and final Brix readings gave the Brix increments. Just whether the second and third extractions would be profitable commercially as against a single extraction is a question, since over 57 per cent of the sugar available by this procedure was produced in the first cook. The figures also indicate that different batches of bran vary somewhat in their composition; for example, starting with experiment No. 10, Table 10, the bran came from another State.

The isolation of crystalline xylose, after the usual neutralization, evaporation, etc., from the battery extracts, was at first very difficult. Only in one or two cases was there any success, and then only when large volumes of alcohol were employed to precipitate interfering materials. It was concluded that in the pressure cooks, even with such a weak acid, gums and other interfering organic materials were being freed from the bran, and it was their presence that was causing difficulties. Sherrard and Blanco [21] reported a similar difficulty in their experiments upon a pressure hydrolysis of bagasse and cottonseed hulls. La Forge [22] in his work on corncobs showed that when a pressure cook was used on corncobs an excellent gum adhesive was produced.

As had been pointed out by Hudson and Harding [23] and by Markley,[24] a pretreatment of the bran to remove gums was necessary. Also each of these workers resorted to alcohol for success. Monroe [25] demonstrated the advantage of giving corncobs a pretreatment with dilute alkali to remove interfering gums in the production of xylose, although it had been prepared from this source without such a treatment.

III. A MODIFIED PROCESS FOR THE PRODUCTION OF XYLOSE FROM COTTONSEED-HULL BRAN

Profiting by the experience of others, a modified method was developed to produce xylose whereby interferring gums were removed and crystalline xylose was regularly obtained from the pretreated bran without the aid of alcohol. In this method xylose crystallization took place from water solutions.

The commercial bran, 2,000 g, was covered in a 12-liter jar or flask with 9 liters of water and heated for two hours at 20 pounds steam pressure to remove soluble gums and other interfering substances. In cases where less pressure was used, difficulty was encountered in the crystallization of xylose. Apparently the steam pressure treatment at 20 pounds removed those interfering materials which the acid hydrolysis at 10 pounds steam pressure would have yielded later on.

To get the center portion of the charge at a temperature equal to that of the outer portion required considerable time, since the bran seemed to have excellent insulating qualities. Where one is equipped with an autoclave, having circulating pumps or a stirring device, the length of time necessary for pressure cooks may, in all probability, be diminished by one half.

This first treatment gave an extract containing very little furfural or furfural-yielding material. The solution contained most of the

[21] See footnote 17, p. 337.
[22] J. Ind. Eng. Chem., **16**, p. 130; 1924.
[23] See footnote 16, p. 337.
[24] See footnote 3 to Table 1, p. 337.
[25] J. Am. Chem. Soc., **41**, p. 1002; 1919.

uncombined soluble ash in the bran in conjunction with the gums, and it was saved for future studies on gums.

The bran was next drained thoroughly, washed and drained, then given an overnight treatment with 5 liters of cold 0.12 *N* sulphuric acid to dissolve the combined ash. When 2,000 g of the bran was drained it retained approximately 3 liters of water or extract, and in making up to volumes and calculating concentrations and yields, this fact was always taken into account.

After this treatment to liberate the bound ash the bran was drained thoroughly, washed and drained. Sufficient dilute sulphuric acid and water were added to make a volume of 6 liters of 0.16 *N* sulphuric acid, sufficient to cover the bran. The charge was then cooked two hours at 10 pounds steam pressure. The extracts were drained from the bran, cooled, and a Brix reading made. These Brix readings averaged 7.5. A second extraction of this bran with dilute sugar extracts (wash waters) at a concentration of 0.16 *N* acid, as in a battery process, gave very low Brix increments. But if fresh 0.16 *N* acid was used upon such bran that had been washed free from the absorbed hydrolysate, appreciable amounts of xylose were obtained in the second extraction. However, when sugar extracts were added to fresh precleaned bran and the whole made up to 0.16 *N* sulphuric acid and this procedure repeated, each time on fresh bran, concentrated sugar solutions were built up. To cite one case, by carefully manipulating wash liquors as in a battery process, an extract having a Brix of 17.2 was obtained when four 2,000 g batches of precleaned bran were successively hydrolyzed. The increments in Brix readings were 7.5, 5.0, 4.5, and 4.5.

The hydrolysate contained sugar, xylans, furfural, mineral acid, organic acids, and considerable colloidal and coloring materials. To clarify the extract and further hydrolyze the xylans, 2 per cent by weight of decolorizing carbon was added and the whole cooked one hour at 10 pound steam pressure. If the extract was filtered hot, on subsequent cooling a turbidity appeared. This, however, did not interfere, and when removed later, by filtration, a clear straw-colored sirup was obtained. The presence of furfural and volatile organic acids in the dilute acid sirup gave trouble in the next steps, therefore they were partially removed when the solution was evaporated in vacuo to one-half of its original volume. Even though this evaporation increased the acidity of the solution to 0.32 *N*, practically, there was no furfural produced, while the bothersome compounds were steam distilled. Also, there was the added advantage in having smaller volumes and lesser amounts of dissolved products of neutralization when the cold hydrolysate was neutralized with powdered calcium carbonate to pH 3.0.

In order to ascertain the effect of hydrogen ion concentration on the amount of calcium going into solution during the neutralization of sulphuric acid in the sugar hydrolysates the following experiment was carried out. To several 25 ml portions of the warm decolorized sugar extract containing 0.14 *N* sulphuric acid [26] calcium carbonate was slowly added until the approximate pH values were reached. The solutions were allowed to stand over night and the following morning colorimetric pH determinations were carefully made. They were then filtered and the insoluble residues washed, ignited, treated

[26] Extract titrated to first color change of thymol blue indicator for sulphuric acid present.

with sulphuric acid, and again ignited. To the filtrates, oxalic acid was added to precipitate the calcium completely. The calcium oxalate was filtered, washed, and ignited. The results were calculated as calcium sulphate. They were plotted in the graph against the pH values. The marked increase of calcium going into solution above pH 3.0, as shown by Curve I (fig. 1), is indicative of the organic acids present. The gradual increase of calcium as shown by Curve II is to be expected, since with increasing pH values greater amounts of insoluble calcium carbonate had to be added to obtain these pH values.

That all the nonvolatile mineral acids present were completely neutralized between pH 2.8 to 3.0 was proved by the fact that evaporations of sugar extracts so neutralized failed to increase in acidity. Because calcium sulphate and calcium bicarbonate are somewhat soluble and thereby cause the sugar sirup to have a high

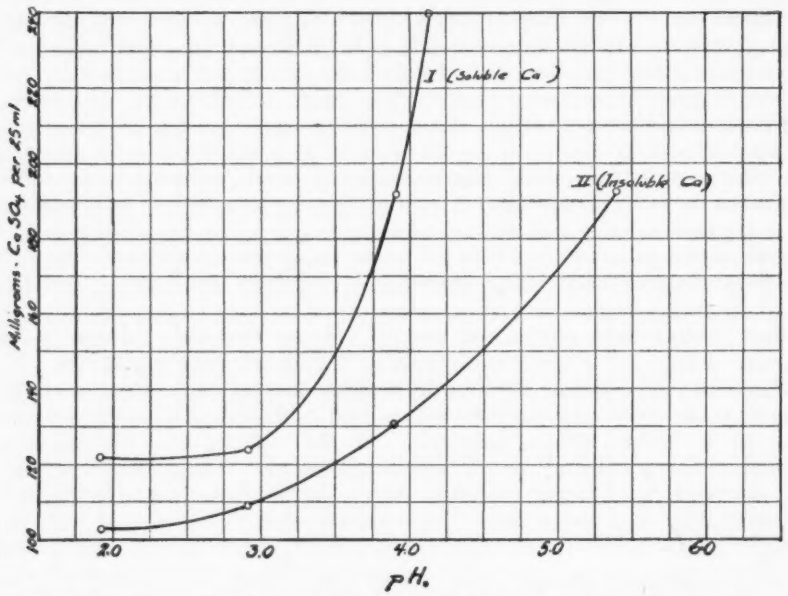

FIGURE 1.—*Neutralization of acid in sugar hydrolysates with calcium carbonate*

ash content, barium carbonate was substituted for calcium carbonate and later a 40° C. saturated solution of barium hydroxide was employed. The approximate amount needed for neutralization was determined by a titration with standard alkali to the first color change of thymol blue indicator. Apparently with careful addition and vigorous stirring, little or none of the xylose was decomposed in the neutralization of the hydrolysates. The use of barium hydroxide gave a solution having a low ash value and eliminated bothersome frothing, while the only difficulty encountered was filtering. Decantation of the settled solution was found to be the simplest procedure.

The presence of traces of furfural caused the sirup to become colored at this step, but the color was easily removed by a cold filtration through a bed of carbon.

The almost water-white sirup was finally evaporated in vacuo to a thick sirup having a specific gravity = 1.35 at 40° C. It had an

amber color and readily crystallized in a beaker almost to a solid mass on standing over night. With the aid of a press the mother liquor was removed and the xylose was dried between filter paper. A 9 per cent yield on the basis of the original weight of the bran was obtained. This product was colored light brown and contained 2 per cent ash. Neutralizations with calcium carbonate gave sugar having 3 to 4.5 per cent ash.

In the purification of xylose by recrystallization nearly 30 per cent of the crude product remained in solution, but since the mother liquors were worked over again the loss was recovered. Three methods of purification were used. One was by recrystallization from water; that is, dissolving the sugar in water at 30° C., decolorizing with carbon (about 1 per cent of the weight of the solution), and evaporating the filtered solution in vacuo on a steam bath to a specific gravity of 1.3, whereby beautiful needlelike crystals were obtained on allowing the sirup to cool slowly. Perhaps an easier method was to make a 60 per cent solution of xylose in water; namely, to heat the water to boiling, add xylose and warm cautiously, decolorize the hot solution with a 1 per cent carbon treatment, and filter quickly. An equal volume of 95 per cent ethyl alcohol was added to this hot solution. In the case of impure products a precipitate was produced and removed immediately by filtration. The solution was set aside in an ice box to crystallize. The alcohol method gave sugar with only a small trace of ash. The third method, namely, crystallization from water solution in the presence of acetic acid recommended by Monroe,[27] gave a good product.

Those phases of the procedure described, wherein only water was needed for removal of gums and in the crystallization and recrystallization of xylose, are responsible for success of the investigation.

The principles of the process are now being employed on a semicommercial scale. A cooperative arrangement is now in effect between the National Bureau of Standards, the State of Alabama through her two educational institutions, the University of Alabama and the Alabama Polytechnic Institute, and the Federal Phosphorus Co., of Alabama, in whose plant xylose is being made. It is the aim of this undertaking to produce xylose in 100-pound-per-day quantities.

IV. SUMMARY

In this paper there is presented some of the representative data on the composition of peanut hulls and cottonseed-hull bran. Experimental data show that the ash content of these plant materials is of a threefold nature. (1) The ordinary dirt and dust held mechanically upon the plant surfaces, (2) ash that is loosely bound chemically, and (3) that ash material which is intimately combined in the organic structure of the plants.

Cottonseed-hull bran is an excellent source for xylose, and peanut hulls and cottonseed-hull bran are rich in furfural-yielding materials.

An improved method, with commercial possibilities for the production of a pentose sugar, xylose, is described.

WASHINGTON, September 21, 1929.

[27] See footnote 25, p. 340.

DESIGN OF A PORTABLE TEMPERATURE-CONTROLLED PIEZO OSCILLATOR

By V. E. Heaton and W. H. Brattain

ABSTRACT

This paper describes the essential details of a portable shielded temperature-controlled piezo oscillator constant in frequency to better than 1 part in 100,000. The quartz plate is mounted in a special plate holder so that the air gap changes very little as the quartz plate shifts in the holder. The plate holder is mounted in a thermal attenuating chamber consisting of a copper cylinder and layers of asbestos contained in a wooden box. The copper cylinder is mounted on heavy bronze coil springs to absorb shocks. A sensitive mercury thermostat, placed in a slot in the side of the copper cylinder, controls the temperature. The heater operates on 110 volts d. c. The quartz plate is connected between the grid and the filament of the oscillator tube. An inductor having a natural frequency slightly higher than that of the quartz plate is used in the plate circuit of the tube. The load is kept constant by loosely coupling to the output through a screen-grid radio-frequency amplifier.

Measurements on the piezo oscillator give the following results: Temperature coefficient of 0.0025 per cent per degree centigrade; 10 per cent variation of plate or filament voltages from operating point of the oscillator tube causes less than 1 part in 1,000,000 change; jarring has no measurable effect on the frequency.

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I. INTRODUCTION

There is considerable demand for a portable temperature-controlled piezo oscillator of a high degree of constancy. As a result of considerable experimentation the bureau has made several portable temperature-controlled piezo oscillators, which on preliminary tests have remained constant in frequency to 1 part in 100,000. In order to obtain this constancy, careful consideration in design is necessary, especially in the small details.

A description of the essential details of these piezo oscillators is the purpose of this paper. However, anyone wishing to construct such a piezo oscillator will find it necessary to overcome many small difficulties before he obtains, as a finished product, a good portable piezo oscillator. The apparatus is described in three parts—circuit arrangement, temperature control, and quartz plate with holder.

II. CIRCUIT ARRANGEMENT

There are a number of circuit arrangements that might be used in the construction of a piezo oscillator. The one chosen had been found previously to be satisfactory and in this work no attempt was made to compare the various types. A description of various circuit

arrangements may be found in an article by A. Crossley.[1] The arrangement chosen is shown in Figure 1.

The quartz plate is placed between the grid and the filament of the oscillator tube and the inductance necessary to produce oscillation is placed in the plate circuit. This inductor is chosen with inductance and distributed capacity so that it has a natural frequency slightly higher than the frequency of the quartz plate without requiring any additional capacity to be shunted across it. A coil having low distributed capacity is best, since it emphasizes the harmonics. A grid

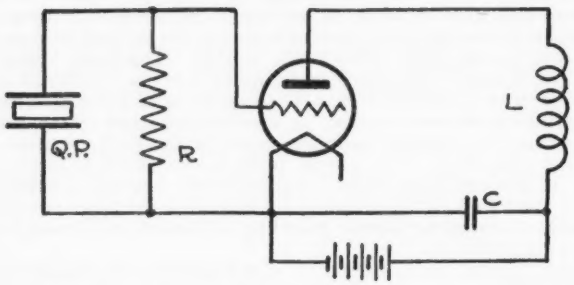

FIGURE 1.—*Simple piezo oscillator circuit diagram.*

resistor of several megohms, placed in parallel with the quartz plate, serves to maintain a constant grid voltage on the oscillator tube.

The output from the piezo oscillator should not be used directly because a variable load at the output will cause a small variation in the frequency. To avoid such variations a constant output is used by means of a constant coupling to a radio-frequency amplifier. This amplifier may consist of one or more stages, depending on the amount of output desired. The coupling to this amplifier should be very loose in order to prevent a possible variation in frequency

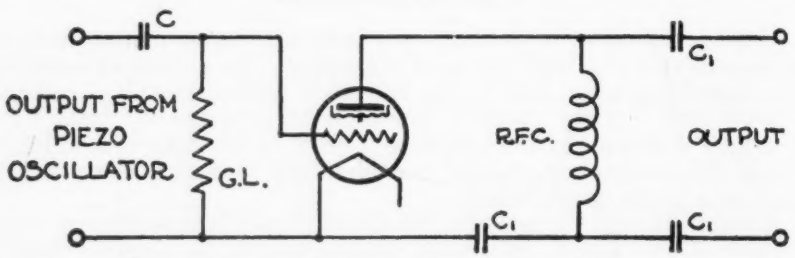

FIGURE 2.—*Radio-frequency amplifier circuit diagram*

of the piezo oscillator due to changes in the amount of power taken from the output of the amplifier. This coupling may be either capacitive or inductive.

A capacitive coupling is chosen as shown in Figure 2. This makes it a simple matter to change the amount of coupling and it also conserves space. The output circuit of this radio-frequency amplifier is a filter circuit consisting of a radio-frequency choke coil and two condensers. The direct current passes through the choke coil, while

[1] Proc. I. R. E., **15**, p. 9; 1927.

the radio-frequency current passes through the condenser to the output terminals. A screen-grid tube is used in the radio-frequency amplifier to prevent changes in the plate circuit from being reflected back into the grid circuit, consequently changing the frequency of the piezo oscillator.

There is also the possibility of external influences affecting the piezo oscillator frequency directly by means of stray coupling, and therefore all the radio-frequency circuits of both the oscillator and the amplifier are thoroughly shielded by placing them in an aluminum cabinet with each joint connected by a brass angle. Thus it is necessary that all parts of the circuits except the quartz plate and instruments be mounted on a bakelite subpanel which can be placed inside the cabinet after most of the wiring is done. The filament and plate voltages are carried from the outside through a cable to the place where these leads are soldered to the circuit. All connections inside the piezo oscillator are soldered securely. Radio-frequency choke coils are placed in each of the positive B battery

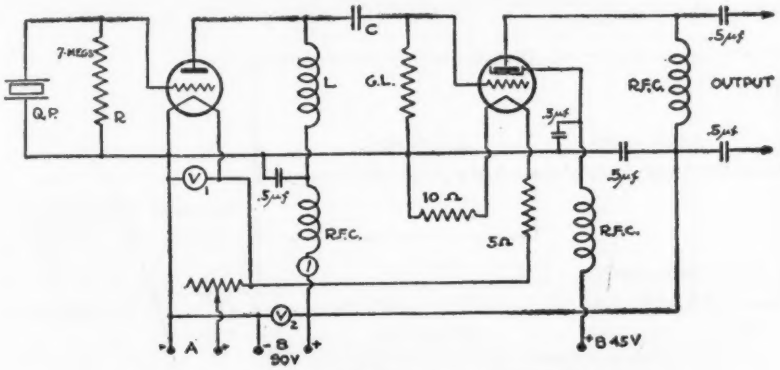

FIGURE 3.—*Complete piezo oscillator circuit diagram*

leads and the radio-frequency current is by-passed by fixed condensers.

The entire circuit arrangement is shown in Figure 3. The resistance R across the quartz plate QP is 7 megohms. The oscillator tube is of a 201–A type. Voltmeter V_1 is used to aid in adjusting the filament voltage. The inductor L is a honeycomb coil. As mentioned above, its inductance and distributed capacity give it a frequency above that of the quartz plate. This difference in frequency is important and should be such that the quartz plate will oscillate freely, but so that its amplitude of oscillation will not be very large. The voltmeter V_2 indicates the plate voltage on the oscillator tube, and a 0 to 5 milliammeter, MA, serves to indicate whether or not the quartz plate is oscillating.

The amplifier is coupled to the oscillating circuit through the condenser C. A screen-grid tube is used in the amplifier, with 5 and 10 ohm resistors to give both the proper grid bias and to adapt this 3-volt tube to the 5-volt filament supply. The radio-frequency choke coils RFC have 60 to 85 millihenries inductance each with low internal capacity.

III. TEMPERATURE CONTROL

A mounted quartz plate has a temperature coefficient of frequency, the amount of which depends on the orientation of the plate with respect to the crystal axes and on the air gap between the metal electrodes and the quartz plate. The magnitude of this temperature coefficient of frequency for "Curie cut" quartz plates is of the order of 0.001 to 0.003 per cent per degree centigrade. Variations in temperature with ordinary thermostatic control are usually a few tenths of a degree centigrade. These variations include long-period changes resulting from gradual aging of the thermostat, short-period changes resulting from amplitude of operation of the thermostat, and variations of temperature with position in the temperature-controlled region. It is obvious, therefore, that in order to insure a constancy of 1 part per 100,000 an improved control had to be used.

The changes in the point at which the thermostat operates may usually be reduced to a negligible amount by a properly designed and aged mercury thermostat. The short-period changes can be greatly decreased by the method of attenuation as described by

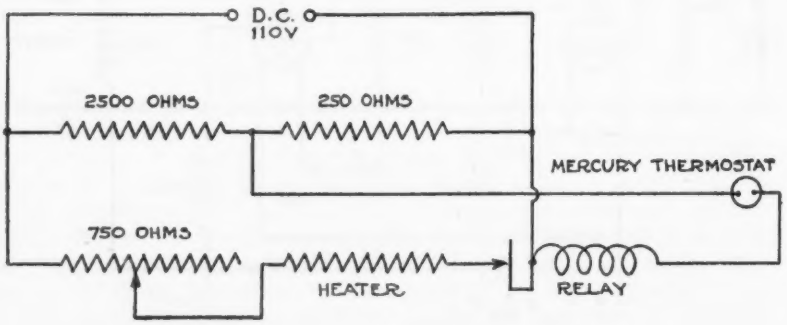

FIGURE 4.—*Temperature-control circuit diagram*

W. A. Marrison.[2] The essentials of the method are, first, a thermostat that will hold its operating temperature to within very narrow limits; and, second, a heating system such that the frequency of operation of the thermostat will be of the order of once a minute; and, third, a thermal attenuation which will reduce the effect of the amplitude of thermostat operation. The variations with position in the thermostatically controlled chamber may, of course, be eliminated by fixing the position of the quartz plate in this chamber.

In the construction of the piezo oscillators described here, a heat-insulated box is made with walls of ½-inch pine and ½-inch balsa wood. A hollow copper cylinder three-eighths of an inch thick is placed inside of the heat-insulated box. The copper cylinder is mounted on heavy bronze coil springs which serve to absorb shocks. The outside of the cylinder is covered with a thin layer of asbestos for insulation, and then is wound with nichrome wire, which serves as the heating unit. The nichrome wire is wound so that there are more turns per unit length on each end than in the middle of the cylinder in order to compensate for the heat losses through the ends

[2] Thermostat Design for Frequency Standards, Proc. I. R. E., **16**, p. 976; July, 1928.

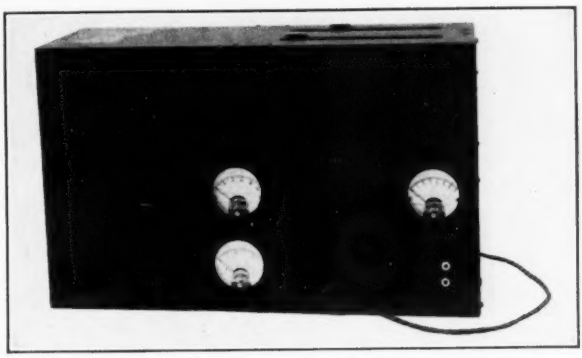

FIGURE 5.—*Front view of the piezo oscillator*

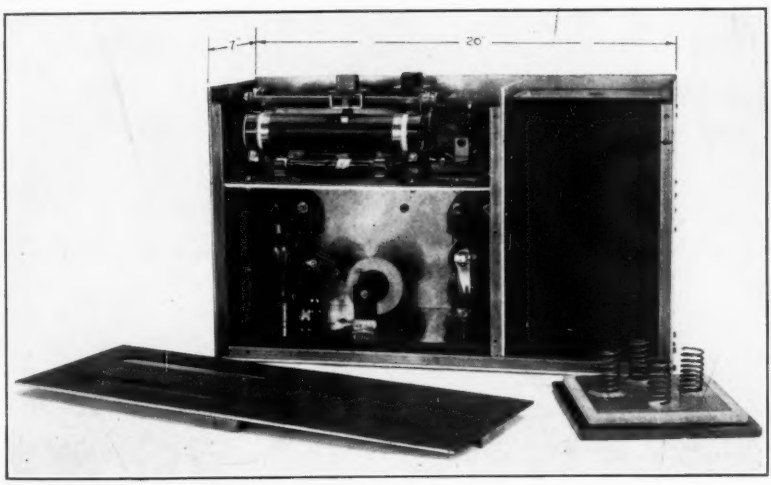

FIGURE 6.—*View of the piezo oscillator with the back removed*

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FIGURE 7.—*The quartz plate holder, mercury thermostat, and the attenuating cylinder*

of the cylinder. A mercury thermostat is used to control the heating current. This thermostat has a sensitivity of 4° C. per inch of bore. The thermostat is placed in a groove in the copper cylinder under the heating wire and in close thermal contact with it. A hole drilled deep into the wall of the copper cylinder and parallel to its axis serves as a thermometer well. The inside of the cylinder is lined with asbestos three-eighths inch thick. Lengthwise of the copper cylinder the space is broken up into three compartments by asbestos disks. The quartz plate and holder are placed in the central compartment and the other two serve to decrease the end effects. The heating unit operates on 110 volts d. c. The temperature-control circuit, shown in Figure 4, is so designed that the mercury thermostat when closed allows a current of 8 milliamperes to flow through the relay which opens the heater circuit. This arrangement is used so that the voltage across the terminals of the thermostat when open is small. The thermostat, by means of the relay, turns on and off the entire heating current. This increases the frequency of operation of the thermostat and makes the temperature inside the cylinder independent of large variations in outside temperature. The 750-ohm rheostat is set so that the length of the period that the heating current is on is approximately equal to the length of the period that it is off.

The copper cylinder and one electrode of the plate holder are grounded to the aluminum cabinet. The other lead is brought out at the bottom of the cylinder and is well insulated. Since this lead is entirely surrounded by a conductor, the capacity between it and the conductor is independent of the position of the lead. The construction of the heating chamber is shown in Figure 7.

IV. QUARTZ PLATE

Mounting.—The quartz plate controls the frequency of the system, and it is obvious that extreme care must be taken in its construction and mounting. Any good quartz plate with a good type of plate holder can be used, but the holder must be of a nature suitable for a portable instrument. The essentials are a quartz plate cut so that it is a good oscillator and so that it oscillates at a single frequency in the immediate range of the frequency desired, and mounted in such a way that the change in frequency due to change in position of the quartz plate is very small. The spacer of the two electrodes must have a small temperature coefficient of expansion so as to diminish that part of the temperature coefficient of frequency which is due to the change in air gap.

The quartz plate actually used is cut as a cylinder, the cut used being the "Curie cut." The dimensions are such that its thickness frequency corresponds to the required value. Care is taken to grind the two ends of the plate flat and parallel. The holder consists of two metal electrodes separated by means of a pyrex ring. The surfaces of the electrodes are ground flat and the edges of the pyrex ring are ground flat and parallel. The diameter of the pyrex ring is chosen so as to fit the cylindrical quartz plate to within one-hundredth of an inch. Care in making the various surfaces flat and parallel assures that motion of the plate in the plate holder will not change the spacing and thereby change the frequency.

The pyrex ring is constructed thicker than the quartz plate so as to prevent the top electrode from touching the quartz plate. The amount of spacing or air gap is determined so that it is approximately one-fourth of a wave length of the supersonic sound waves generated by the quartz plate.[3] The exact spacing is unimportant as long as it is between zero and one-half wave length and is uniform throughout the space occupied by the crystal. A photograph of the mounting is shown in Figure 7.

V. RESULTS

Six of these piezo oscillators have been built in the past 18 months and thoroughly tested. The tests that were made on these piezo oscillators were: Determination of temperature coefficient of frequency; measurement of the variation of frequency due to variations in either plate voltage or filament voltage on the oscillator tube; measurement of the variation in frequency due to shocks and to moving; and measurements of the frequency periodically for several months.

The results of such tests in the case of the piezo oscillator described here are: Temperature coefficient, 0.0025 per cent per degree centigrade; 10 per cent variation of plate and filament voltages from operating point on oscillator tube (201A) causes less than 1 part in 1,000,000 change; jarring the piezo oscillator has no measurable effect; tipping and moving it around causes a variation of frequency of approximately 7 parts in 1,000,000. Finally, measurements taken once every day over a period of three months without disturbing the piezo oscillator show variations less than 5 parts in 1,000,000. It is possible that there may be a drift in frequency over a long period, but no experimental evidence of such a variation has been found.

WASHINGTON, August 8, 1929.

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[3] Piezo-Electric Quartz Resonator and Equivalent Electrical Circuit, by D. W. Dye, Phys. Soc. Proc. **38**, pp. 399–457; 457–458; August, 1926. Elect. Rev., **99**, pp. 733–735; October 29, 1926. Notes on Quartz Plates, Air Gap Effect, and Audio-Frequency Generation, by A. Hund, Proc. I. R. E., **16**, pp. 1072–78; August, 1928.

A 12-COURSE RADIO RANGE FOR GUIDING AIRCRAFT WITH TUNED REED VISUAL INDICATION

By H. Diamond and F. G. Kear

ABSTRACT

This paper describes a radio-directive beacon (or radio range), of the visual-indicating type, which has been developed by the National Bureau of Standards to provide radio-marked courses at air terminals where more than four airways converge.

The radio range is similar in design to the double-modulation type with the addition of a third amplifier train and accompanying modulation frequency. It provides 12 equisignal zones which may be oriented within rather wide limits and made to coincide with the converging airways.

In order to prevent coupling between amplifier branches special means are employed to supply them successively rather than simultaneously. These are described in detail and the stability of the resulting system is shown to be excellent.

Three-phase radio-frequency supply is used to excite the amplifier trains, which is received from a single-phase oscillator of conventional type by means of a phase divider. This prevents possible trouble due to the employment of a 3-phase oscillator with 3-tuned oscillating circuits.

To transfer the energy to the antenna system a goniometer with three primary coils is employed. These are displaced 120° from each other and coupled to the two crossed loop antennas through two secondary coils whose displacement is 90°. This permits the use of two antennas to establish a space pattern from three amplifier branches.

Means for aligning this resultant space pattern with the airways are also discussed and several examples are given.

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I. INTRODUCTION

The rapid increase in the number of airways emanating from the more important airports of the United States has created a need for a directive radiobeacon capable of marking out a greater number of courses than has hitherto been possible. This paper describes a radio range (that is, directive radiobeacon) which provides 12 beacon courses normally disposed 30° from each other. By means of simple adjustments at the transmitter the angles between courses can be set as desired. This range fulfills all the present requirements for guiding aircraft along the civil airways.

The 12-course radio range is similar in operation to the 2 and 4 course radio ranges previously described.[1] The increase in apparatus

[1] J. H. Dellinger and H. Pratt, Radio Aids to Air Navigation, Proc. Inst. Radio Engrs., **16**, pp. 890–920; July, 1928. J. H. Dellinger and H. Diamond, Radio Developments Applied to Aircraft, Mech. Eng., **51**, No. 7, pp. 509–514; July, 1929.

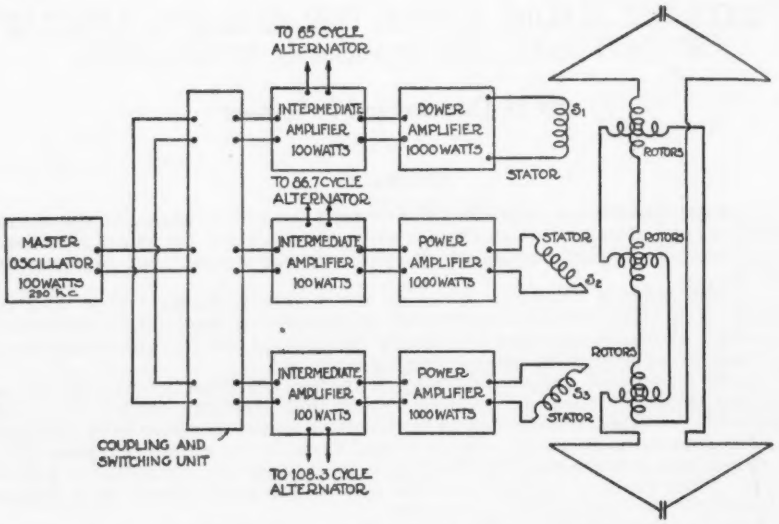

FIGURE 1.—*Schematic diagram of 12-course radio range*

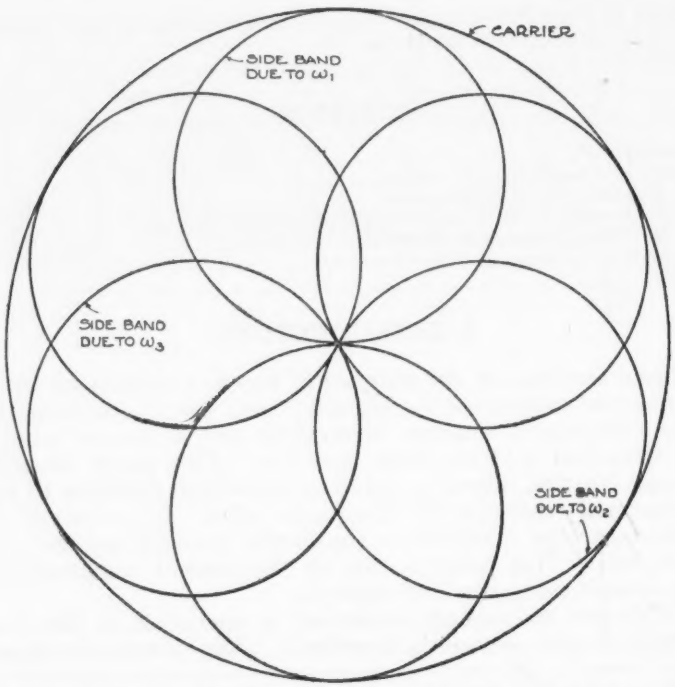

FIGURE 4.—*Space pattern radiated by 12-course radio range (link circuit type)*

FIGURE 2.—*Experimental 12-course range transmitter installed at College Park, Md.*

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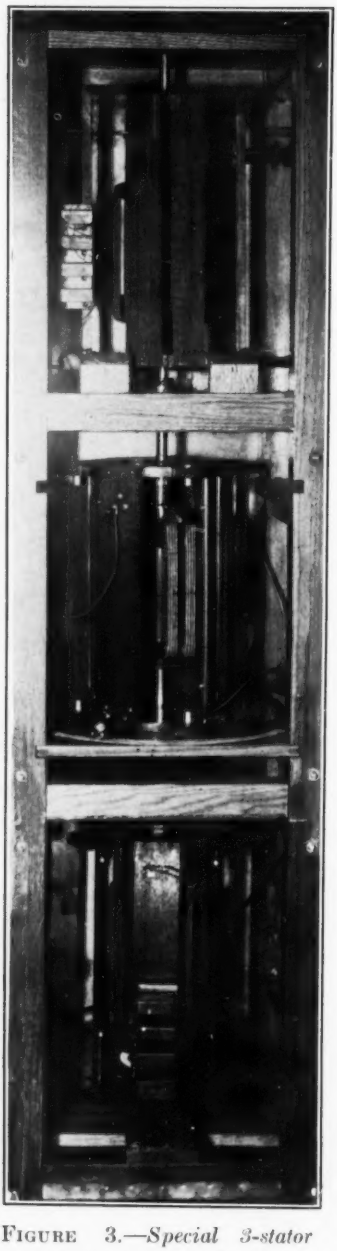

FIGURE 3.—*Special 3-stator goniometer employed with 12-course radio range*

is not great. The same crossed-coil antenna system and the same circuit arrangements are employed (see fig. 1), except that three amplifier branches modulated to three different low frequencies are necessary. The modulation frequencies used are 65, 86.7, and 108.3 cycles, respectively. In addition a special goniometer is required. The rotor system of this goniometer comprises two coils crossed at 90°, and each connected in series with one loop antenna. For convenience in goniometer design each rotor coil is made up of three sections. Three stator coils, normally placed at 120° with each other, are employed, one stator coil being connected to each power amplifier tube of the transmitting system.

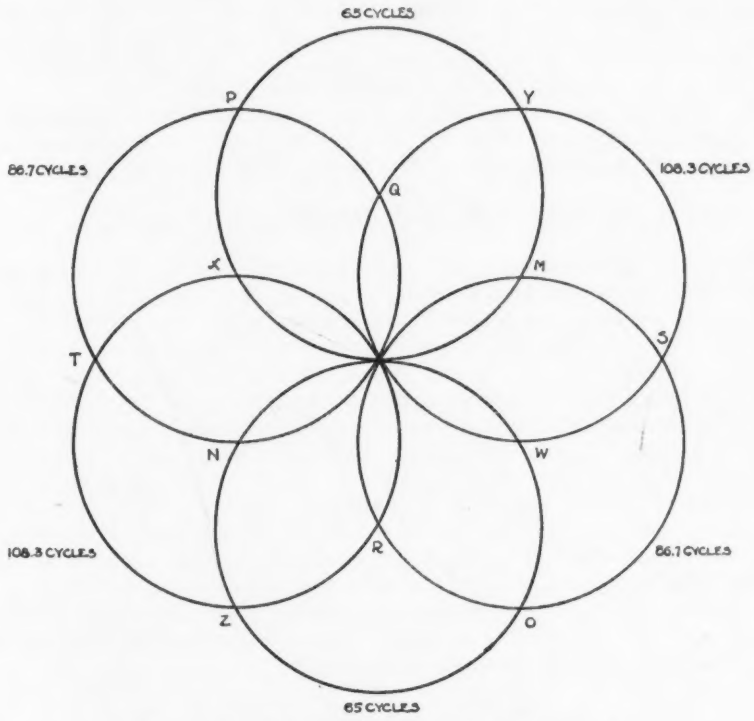

FIGURE 5.—*Polar pattern as received on the reeds*

A photograph of the 12-course beacon transmitter installed at College Park, Md., is shown in Figure 2. Figure 3 is a photograph of the special goniometer employed.

Referring to Figure 1, it will be observed that stator coil S_1 carries a radio-frequency current modulated to 65 cycles, stator coil S_2 carries a radio-frequency current modulated to 86.7 cycles, and stator coil S_3 a radio-frequency current modulated to 108.3 cycles. Each stator coil, acting in conjunction with the two crossed rotor coils and the two crossed loop antennas, sets up a system which is electrically equivalent to a single loop antenna. The plane of this phantom antenna coincides with the plane of the stator winding for zero setting of the rotor, but rotates in space as the rotor system is rotated.

Since there are three stator coils, placed at 120° with each other, three such phantom antennas (crossed at 120°) exist. When special precautions are taken in circuit design the combined space pattern consists of a circular carrier with three figure-of-eight side bands crossed at 120°. (See fig. 4.) The corresponding polar pattern as received on the reeds is shown in Figure 5.

Now assume that a pilot is equipped with three vibrating-reed course indicators of the 2-reed type,[2] the first tuned to 65 and 86.7 cycles, the second to 86.7 and 108.3 cycles, and the third to 65 and 108.3 cycles, respectively. Using the first indicator, he will find four courses at *M*, *N*, *O*, and *P*. With the second course indicator he will observe four courses at *Q*, *R*, *S*, and *T*. Similarly, with the third reed indicator, four courses at *W*, *X*, *Y*, and *Z* will be obtained. Two of each set of four courses (for example, *M* and *N*) have an equisignal zone of 1° to 1.5° wide, while the width of this zone for the other two courses (viz, *O* and *P*) is from 3° to 4°.

To simplify the use of this beacon, a special 3-reed indicator for receiving all 12 courses of the beacon without confusion has been developed.[3] A photograph of this indicator is given in Figure 6.

II. THEORY OF 12-COURSE RADIO RANGE

Since the goniometer stator windings are not at 90° with each other (see fig. 1) undesirable intercoupling between S_1, S_2, and S_3 will exist, resulting in a combined beacon space pattern which can not be used. Direct inductive coupling between stator windings is eliminated by the use of the 3-section rotor system, each stator winding being placed in a separate shielded compartment. Indirect coupling between stator windings by virtue of their mutual induction with the rotor system still exists. This coupling is somewhat more difficult to eliminate. By setting up the circuit equations for the goniometer system when no precautions are taken to prevent this coupling, and solving for the currents in S_1, S_2, and S_3, two facts may be determined: (1) That the radio-frequency current in each stator winding is modulated to all three modulation frequencies of the beacon, (2) that the amount of coupling between stator windings is independent of the rotor setting. Several arrangements are possible for preventing this undesirable intercoupling.

1. LINK CIRCUIT ARRANGEMENT

One arrangement consists of neutralizing this coupling by introducing inductive coupling between stator windings of opposite sense, as shown in Figure 7. Thus S_1 is coupled to S_2 by coils $L_1L_1''L_2'L_2$ and to S_3 by coils $L_1L_1'L_3''L_3$. Similarly, S_2 is coupled to S_1 as noted and to S_3 by coils $L_2L_2''L_3'L_3$. The link circuits $L_1''C_1L_2'$, $L_2''C_2L_3'$, and $L_3''C_3L_1'$ are each tuned to the beacon carrier frequency. It is evident that by virtue of these link circuits a current flowing in any stator induces in each of the other stators an e. m. f. 180° out of phase with that current. On account of the indirect coupling between stators by way of the rotor system a current flowing in any

[2] F. W. Dunmore, Design of Tuned-Reed Indicators for Aircraft Radio Beacon, B. S. Jour. Research: November, 1928. (Research Paper No. 28.)
[3] F. W. Dunmore, A Tuned Reed Course Indicator for the 4 and 12 Course Aircraft Radio Range, B. S. Jour. Research.

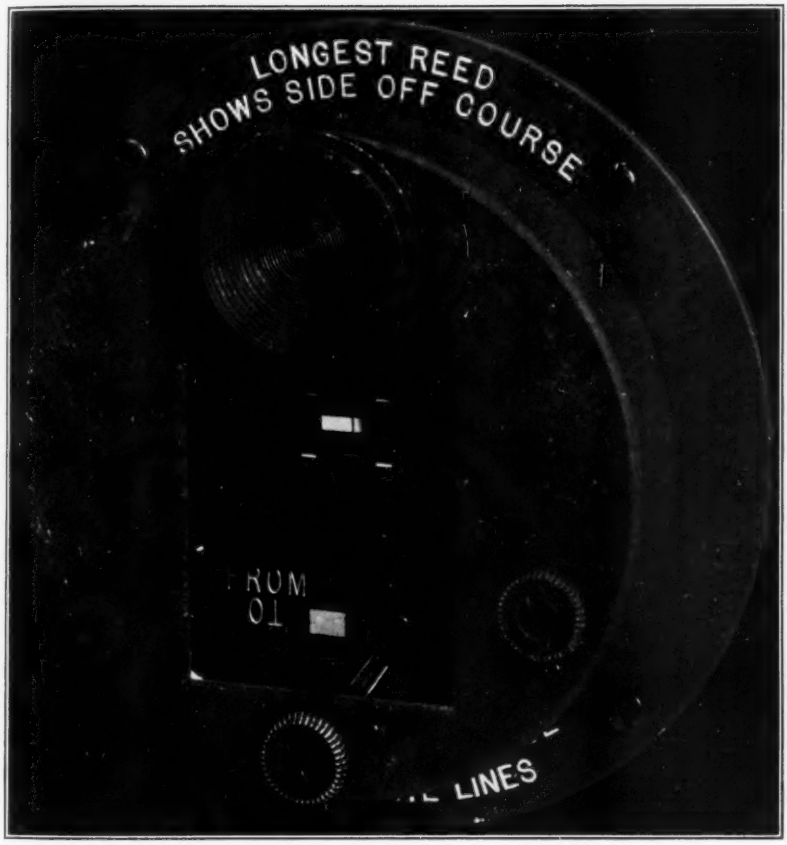

FIGURE 6.—*Special course indicator for 12-course radio range*

one stator induces in each of the other stators a voltage exactly in phase with that current. By properly adjusting the amount of coupling due to the link circuits an exact neutralization may be obtained.

The carrier-frequency currents in S_1, S_2, and S_3 (fig. 1) have been assumed to be in time phase. Since the stator windings are displaced by 120° space phase the resultant carrier transmitted is zero. A circular carrier can, however, be supplied by the use of a vertical antenna extending along the beacon tower and coupled through a 50-watt amplifying tube to the master oscillator of the beacon trans-

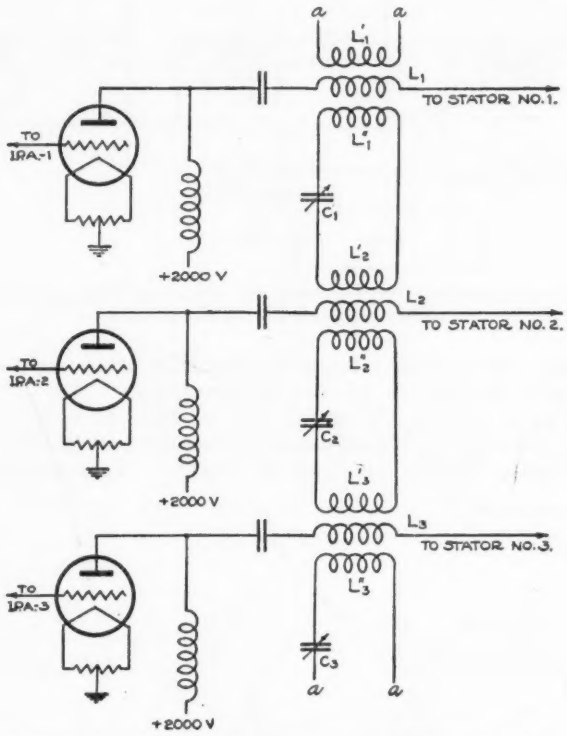

FIGURE 7.—*Link circuit arrangement for preventing intercoupling between primary goniometer windings*

mitting set. For optimum results, this antenna must be in accurate tune to the beacon carrier frequency. The polar patterns shown in Figures 4 and 5 are for this transmitting arrangement.

2. AUTOMATIC SWITCHING USING 3-PHASE GRID-BIASING

The use of link circuits to eliminate coupling between stator windings and the need for supplying an auxiliary carrier to replace the one supressed by the goniometer system may both be precluded if means are provided for exciting but one stator winding at a time. The complexity of the scheme outlined above led to experiments toward devising such means.

An obvious arrangement for accomplishing this consisted of inserting a commutator carrying three segments occupying successive 120° arcs in the supply leads from the master oscillator to the grids of the intermediate power amplifier tubes. In this

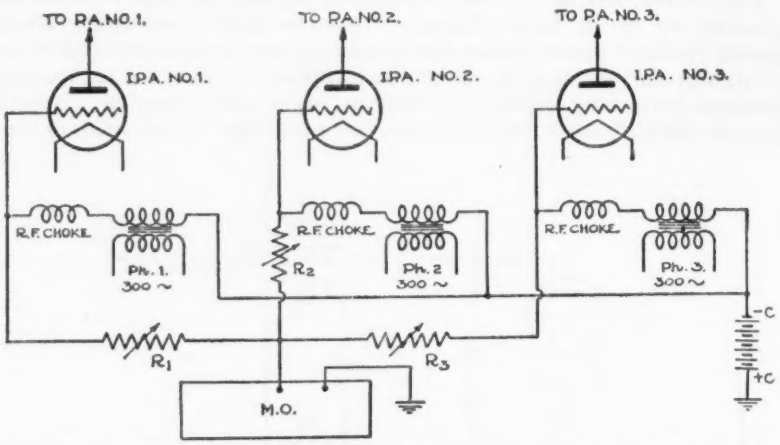

FIGURE 8.—*Grid-biasing arrangement for switching radio-frequency supply successively to each amplifier train*

way voltage was supplied to each amplifier train only during one-third of each revolution of the commutator. The switching was performed at a sufficiently rapid rate so that in spite of the interruptions in the signals transmitted the reeds maintained their vibration amplitudes due to mechanical inertia, This method had two

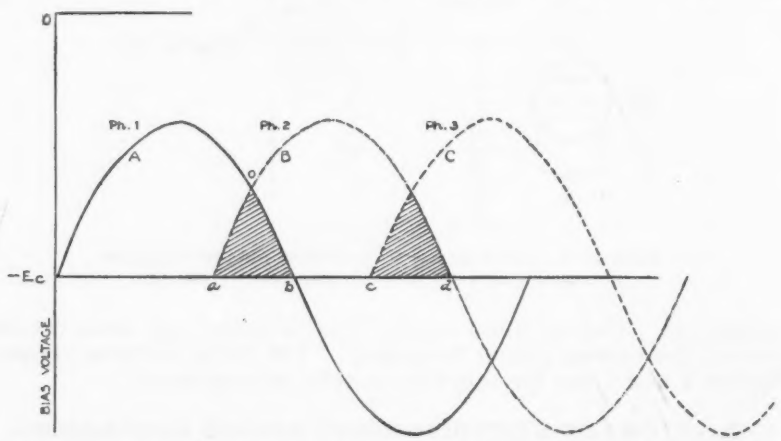

FIGURE 9.—*Resultant biasing voltages on grid of each intermediate-amplifier stage*

distinct disadvantages: (1) The power transmitted by each amplifier train was reduced to one-third normal, and (2) surges in the transmitted wave due to high-speed switching resulted in shock excitation of the reeds used for reception, the net effect in the beacon operation being a virtual widening of the equisignal zones.

The next circuit arrangement used proved considerably more successful, the switching of power being performed at an audio-frequency rate by means of the circuit shown in Figure 8. A d. c. biasing voltage, common to the grid circuits of the three intermediate amplifying tubes, is employed and is of such magnitude that (in the absence of the 3-phase 300-cycle supply) no power is transmitted through these tubes. In series with this common d. c. biasing voltage, each grid circuit has induced in it one of the phase voltages of the 3-phase 300-cycle supply. The resultant biasing voltages impressed on the grid of each of the three intermediate amplifying tubes are indicated by curves *A*, *B*, and *C*, respectively, of Figure 9. Since $-E_c$ is the cut-off voltage, each tube passes

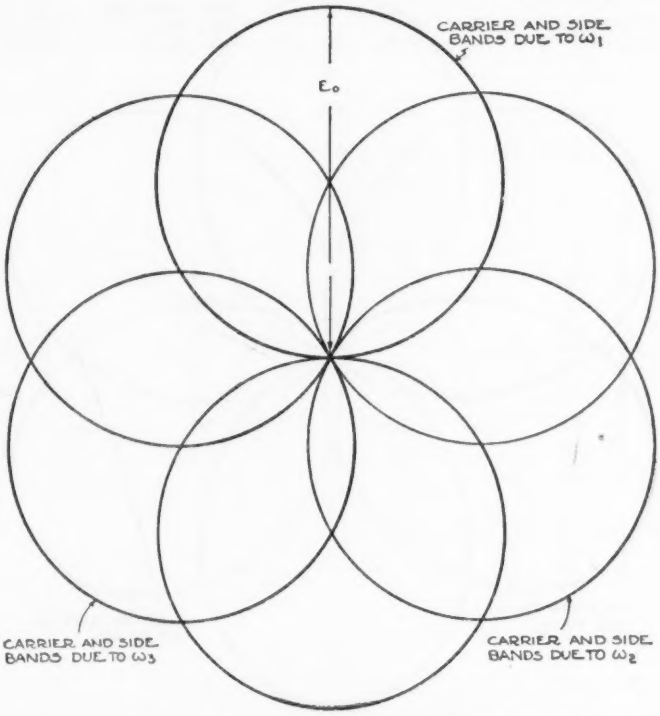

FIGURE 10.—*Space pattern radiated by beacon when using grid biasing arrangement for preventing intercoupling between primary goniometer windings*

power only during the positive half-cycle of its a. c. biasing voltage. As a result no two amplifier tubes transmit power simultaneously except during the small intervals of time *a–b*, *c–d*, etc., as shown in Figure 9. The proportion of power transmitted during these intervals is less than the ratio of shaded area *aob* to total area of transmission per cycle for one tube $E_c aob$, since the tube is then operating on the knee of its characteristic curve. The amount of coupling still present may be further reduced by increasing the common d. c. bias voltage, but this results also in a decrease of total power transmitted. In practice this further reduction is unnecessary, the beacon performance proving satisfactory without it.

Neglecting the small amount of coupling present the beacon space pattern becomes as shown in Figure 10. Note that, since but one stator winding is excited at a time, there are three independent carrier waves in the beacon-space pattern. Assuming square-law detection the polar pattern as received on the reeds is shown in Figure 11.

The choice of frequency of the 3-phase alternator used for the grid bias switching is important. The fundamental and second harmonic of this frequency must not be closer than approximately 20 cycles to any of the harmonics of the modulation frequencies used in the beacon. To illustrate the reason for this requirement

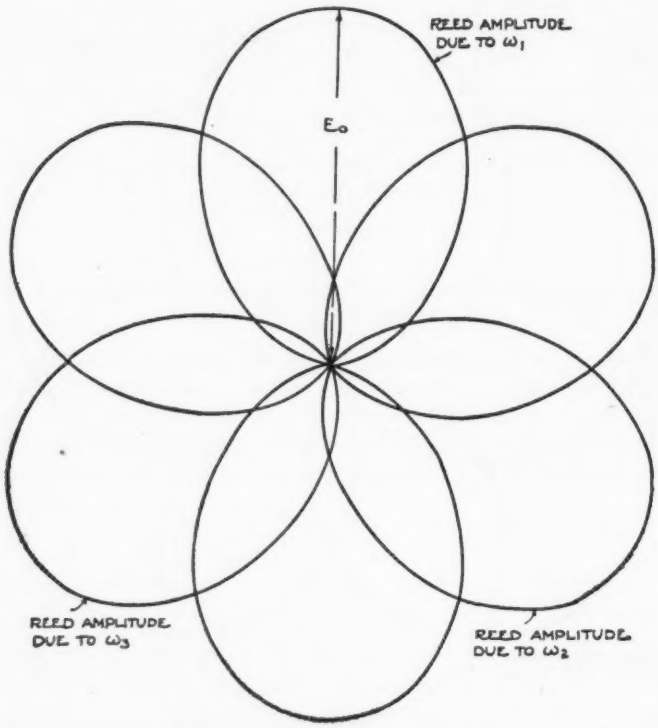

FIGURE 11.—*Received pattern corresponding to space pattern of Figure 10*

assume that a frequency of 262 cycles were chosen for the 3-phase alternator. The fourth harmonic of 65 cycles and the third harmonic of 86⅔ cycles are each 260 cycles. Under this condition a beating of the reed indicator at the difference frequency of 2 cycles is obtained.

The net power transmitted by each amplifier branch when using this method of switching is, of course, reduced considerably below normal; primarily because power is transmitted only during approximately one-half the time, and secondly because during that time the operating point travels along the tube characteristic from the point of cut-off to the point of normal operation and back to the cut-off point. The net reduction in power is, however, not as great as might be expected from the above, since it is possible to force the tubes con-

siderably above normal during the half cycle of operation and still maintain safe average plate dissipation. Using this system, with 8 amperes in each loop antenna, an operating range of 100 miles was obtained.

3. THREE-PHASE RADIO-FREQUENCY SWITCHING

The use of 3-phase audio-frequency for switching the radio-frequency power as described above suggested that the same results could be obtained if a source of 3-phase radio-frequency were available. Each phase of this 3-phase radio-frequency supply could then be used for supplying carrier voltage to the grid of one intermediate amplifier, the 3-phase source thus serving as a master oscillator as well as a switching device. The advantages to be gained are fourfold:

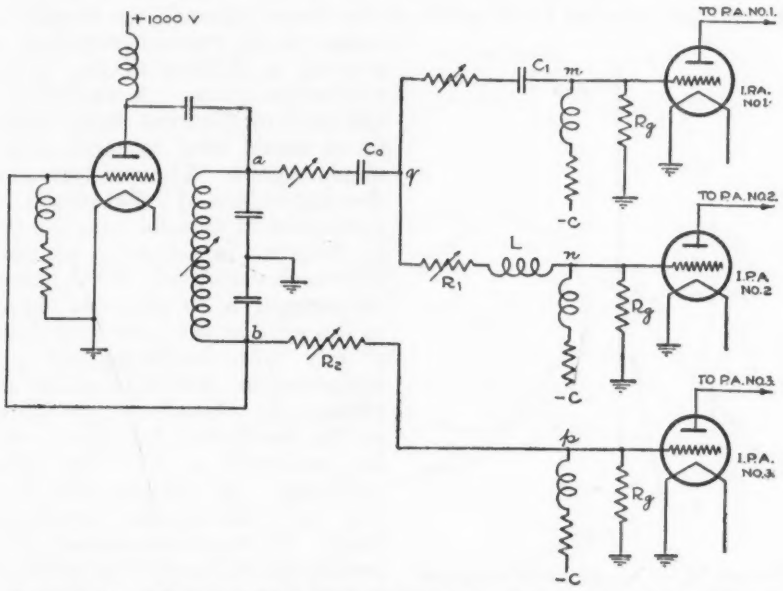

FIGURE 12.—*Phase-splitting arrangement for obtaining 3-phase radio-frequency switching*

(*a*) A decided increase in the power transmitted by each amplifier branch, (*b*) the elimination of a 3-phase audio-frequency unit, (*c*) the operation of the intermediate amplifier tubes under normal conditions and not with the high grid voltages necessary in the method of grid bias switching, and (*d*) the elimination of interference caused by the audio-frequency used for grid biasing.

A 3-phase radio-frequency oscillator of the type described by R. Mesny [4] was constructed to serve as the 3-phase source. However, advantages of simplicity in design and operation led to the development of the phase-splitting arrangement shown in Figure 12.

Referring to Figure 12, a single-phase Colpitts oscillating circuit is employed. Advantage is taken of the fact that the voltages from

[4] R. Mesny, Generation of Polyphase Oscillations by Means of Electron tubes, Proc. I. R. E., 13, pp. 471–476; August, 1925.

points a and b to ground are approximately 180° out of time phase. It is desired that the voltages from points m, n, and p to ground have a 120° time-phase displacement. The values of the condenser, C, and the inductance, L, are so chosen that the voltage from m to ground leads the voltage from q to ground by 60° and the voltage from n to ground lags the same voltage by 60°. The condenser, C_0, is so chosen that the voltage from q to ground is 180° out of phase with the voltage from p to ground. The variable resistances shown aid materially in making these adjustments. The impedances of the various branches must be such that the voltages from m, n, and p to ground are equal in magnitude as well as 120° out of phase. The voltage vector diagram corresponding to this adjustment is shown in Figure 13.

As will be explained below, the time-phase displacement between the voltages applied to the grids of the three intermediate amplifying tubes must remain constant to prevent a shifting of the beacon courses in space. A variation of the grid to filament tube impedances would tend to cause such a displacement. The resistances, R_g (having values of 7,500 ohms) are connected in parallel with the grid to filament impedances to minimize such variation. With this arrangement, a 20 per cent change in the grid to filament impedance of any tube results in but a 2° variation in the time-phase displacement. Similarly, a change in the oscillator frequency of 2 kc. results in a 0.2° time-phase variation. As will be shown, these are well within the permissible limits. The means employed for adjusting the voltages from points m, n, and p to ground to their proper phase relationship is of interest.

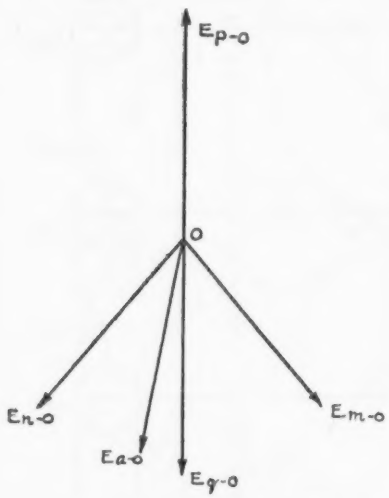

FIGURE 13.—*Voltage vector diagram corresponding to circuit of Figure 12*

The use of 7,500-ohm resistors in parallel with the tube input impedance has already been mentioned. With these resistors in use, the load impedances of the phase divider remain sensibly constant and adjustments can be made on that basis.

First, condensers C_0 and C are short-circuited and the output of the master oscillator is adjusted by raising or lowering its plate voltage until the grid meter in the branch mo reaches a convenient reading, I_0. The current in branch no will then read, say I_1. Condenser C is then inserted in the circuit and its capacity adjusted until the current in the circuit mo is reduced to one-half of its former value. At the same time the master oscillator output is kept constant by keeping the grid current in branch no at I_1. When the current is halved, assuming a purely resistive circuit in the first instance, the phase angle of the voltage mo has been adjusted to a 60° leading angle with the voltage qo.

Next, with C_0 still short-circuited, the process is repeated in the branch *no*, adjustment of L being made until the desired angle is secured. At the same time the resistance R_1 is varied to keep the total circuit impedance the same as that of the condenser branch. This is readily noted from the grid milliammeter readings, which should read the same in both branches.

The voltages *mo* and *no* are now in the correct phase relationship. There remains the selection of the proper value for C_0 in order that *qo* be in 180° time phase with *po*. This adjustment is not as straightforward as the preceding ones.

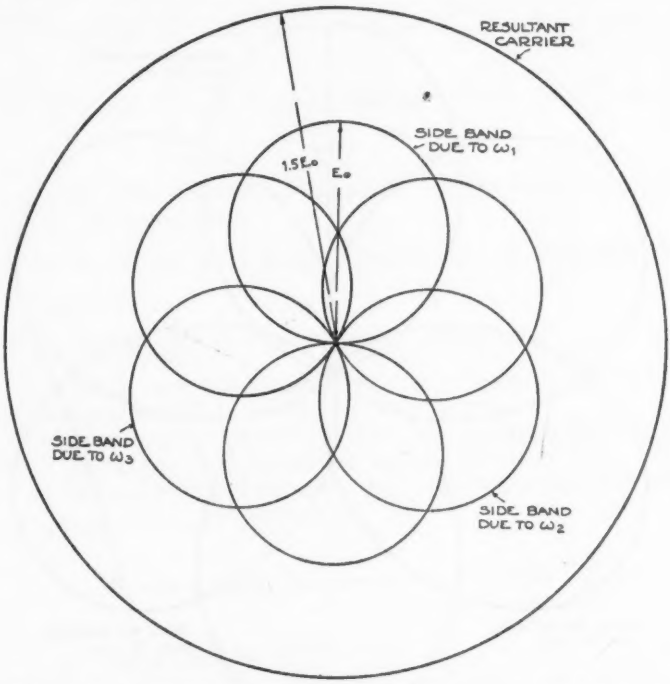

FIGURE 14.—*Beacon space pattern when using radio-frequency switching*

As previously explained, when the phase relations are correct, the carrier may be considered as a rotating figure-of-eight of constant magnitude. This effect is utilized in making the final adjustment.

With d. c. excitation on the plates of the intermediate power amplifier tubes and the condenser C_0 in the circuit, the output of each amplifier branch is separately balanced in magnitude by adjustment of R_2 until all three are equal as shown by the antenna currents. All the branches are then excited through the phase divider and the goniometer rotated. When C_0 is of the correct value the antenna current remains constant for all positions of the rotor. C_0 is, consequently, varied until this constancy of antenna current occurs. A readjustment of R_2 is necessary after each change of C_0 in order that the magnitudes of the three voltages remain equal. The three voltages are now in correct time phase and will not change appreciably

with changes in amplifier load or tube constants encountered in normal operation.

There is one important difference between the radio-frequency method of switching and the audio-frequency grid bias method previously described. In the latter method coupling between stator windings was eliminated because the stators were never excited simultaneously. In the radio-frequency method the coupling is eliminated chiefly due to the time-phase displacement.

The beacon space pattern obtained when using this system and the corresponding received polar diagram are shown in Figures 14 and 15, respectively. Note that even for the same power transmitted

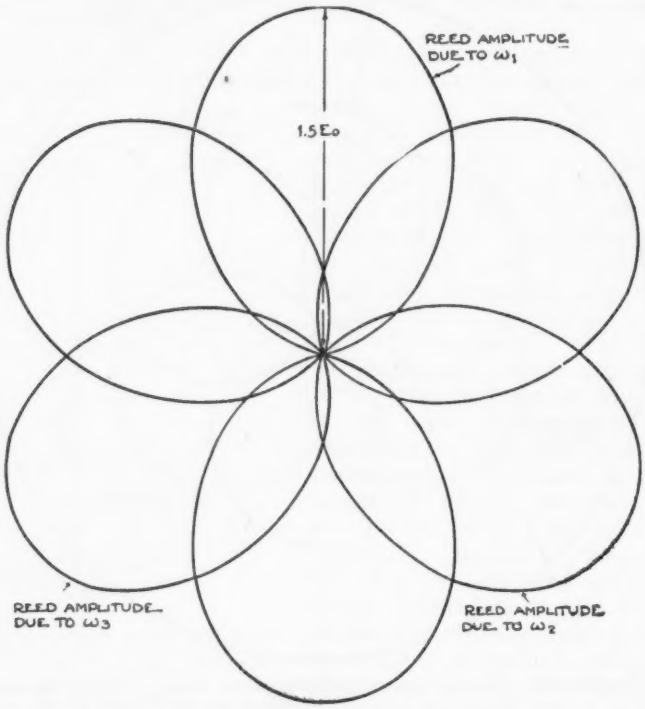

FIGURE 15.—*Received pattern corresponding to space pattern of Figure 14*

by each amplifier branch this system yields 50 per cent greater received signal than the system employing grid-bias switching. The patterns of Figures 14 and 15 are for the special case when the three stator windings are exactly 120° apart in space phase and the three voltages applied to these stators exactly 120° apart in time phase. The general expression for the space pattern for any time phase relationship between these three voltages is given in equation (1). The first term to the right of the equality sign represents the carrier, while the second, third, and fourth terms represent the side bands due to modulation frequencies, ω_1, ω_2, and ω_3, respectively. As will be observed, the carrier comprises a figure of eight revolving in space at the carrier-frequency rate. The curve representing the carrier in

Figure 14 is in reality the locus in space of successive maxima of the rotating figure.

$$e_p = KE_0\left\{\begin{array}{l}\cos\ (\omega t+\Delta_1)\cos\theta+\cos\left(\omega t-\frac{2\pi}{3}+\Delta_2\right)\cos\left(\theta-\frac{2\pi}{3}\right)\\ \quad+\cos\left(\omega t-\frac{4\pi}{3}+\Delta_3\right)\cos\left(\theta-\frac{4\pi}{3}\right)\end{array}\right\}$$

$$+\frac{KE_1}{2}\left\{\cos\ (\omega t+\Delta_1-\omega_1 t)+\cos\ (\omega t+\Delta_1+\omega_1 t)\right\}\cos\theta \qquad (1)$$

$$+\frac{KE_2}{2}\left\{\cos\left(\omega t-\frac{2\pi}{3}+\Delta_2-\omega_2 t\right)+\cos\left(\omega t-\frac{2\pi}{3}+\Delta_2+\omega_2 t\right)\right\}\cos\left(\theta-\frac{2\pi}{3}\right)$$

$$+\frac{KE_3}{2}\left\{\cos\left(\omega t-\frac{4\pi}{3}+\Delta_3-\omega_3 t\right)+\cos\left(\omega t-\frac{4\pi}{3}+\Delta_3+\omega_3 t\right)\right\}\cos\left(\theta-\frac{4\pi}{3}\right)$$

where

(e_p is the field intensity at any point, P, in space as a polar function of the angle θ.

$\frac{E_1}{E_0}\times 100$ is the percentage modulation in amplifier branch 1 due to ω_1

$\frac{E_2}{E_0}\times 100$ and $\frac{E_3}{E_0}\times 100$ have similar meanings.

Δ_1, Δ_2, and Δ_3, are the time-phase displacement angles of the three carrier components from exact 120° relationship.

The corresponding expression for the received polar pattern is given by equation (2), assuming square-law detection. The three terms to the right of the equality sign represent the reed amplitudes due to ω_1, ω_2, and ω_3, respectively.

$$e_r = KK'\left[\begin{array}{l}E_0E_1\cos\omega_1 t\left\{\cos^2\theta+\cos\alpha_1\cos\theta\cos\left(\theta-\frac{2\pi}{3}\right)+\cos\alpha_3\right.\\ \quad\left.\cos\theta\cos\left(\theta-\frac{4\pi}{3}\right)\right\}\\ +E_0E_2\cos\omega_2 t\left\{\cos^2\left(\theta-\frac{2\pi}{3}\right)+\cos\alpha_1\cos\theta\cos\left(\theta-\frac{2\pi}{3}\right)\right.\\ \quad\left.+\cos\alpha_2\cos\left(\theta-\frac{2\pi}{3}\right)\cos\left(\theta-\frac{4\pi}{3}\right)\right\}\\ +E_0E_3\cos\omega_3 t\left\{\cos^2\left(\theta-\frac{4\pi}{3}\right)+\cos\alpha_3\cos\theta\cos\left(\theta-\frac{4\pi}{3}\right)\right.\\ \quad\left.+\cos\alpha_2\cos\left(\theta-\frac{2\pi}{3}\right)\cos\left(\theta-\frac{4\pi}{3}\right)\right\}\end{array}\right] \qquad (2)$$

where e_r is the signal received on the reeds as a polar function of the angle θ.

$$\alpha_1=\frac{2\pi}{3}+\Delta_1-\Delta_2$$

$$\alpha_2=\frac{2\pi}{3}+\Delta_2-\Delta_3$$

$$\alpha_3=\frac{2\pi}{3}+\Delta_3-\Delta_1$$

Reference to Figure 16 will show that α_1, α_2, and α_3 are, respectively, the time-phase displacement in degrees between the three carrier voltage vectors of the transmitting system. The amplitudes of these voltage vectors are in turn space functions of the angle θ. It should be noted that each set of side bands transmitted by one amplifier branch beats with its own carrier and also with the in-phase components of the other two carriers of the system.

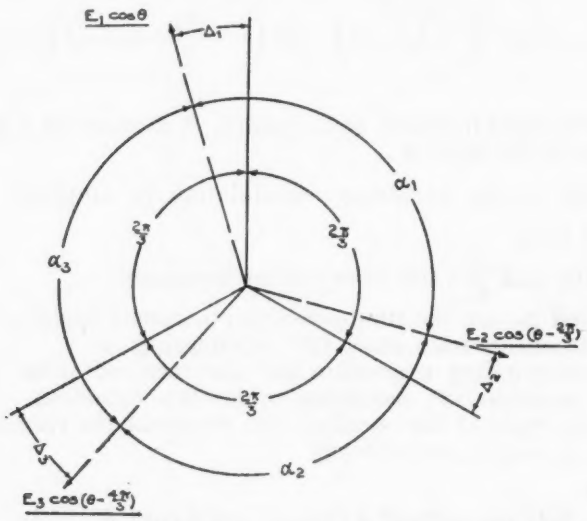

FIGURE 16.—*Graphical interpretation of equation (2)*

As noted above, a departure of the three carrier voltages from exact 120° time-phase displacement results in a shifting of the beacon courses in space. The extent of this shift can be determined by substituting special values for the time-phase displacements in equations (1) and (2) above.

For the conditions

$$\alpha_1=120°$$
$$\alpha_2=150°$$
$$\alpha_3=\ 90°$$

which is equivalent to a 30° time-phase displacement of one of the voltage vectors, the beacon space pattern becomes as shown in Figure 17 and the received pattern as shown in Figure 18. Note that the maximum shift of any course from its normal position is 10°. As noted above, the maximum time-phase variation to be expected, due to variations in the circuit constants, is but 2°. The beacon courses will therefore remain practically fixed in space.

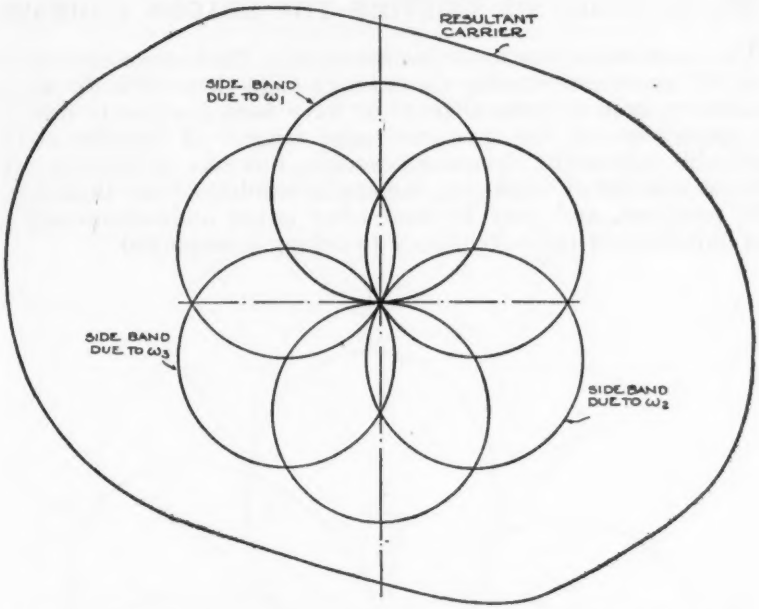

FIGURE 17.—*Beacon space pattern when the time phase of one of the three carrier-frequency voltages of the system is displaced by 30° from its normal value*

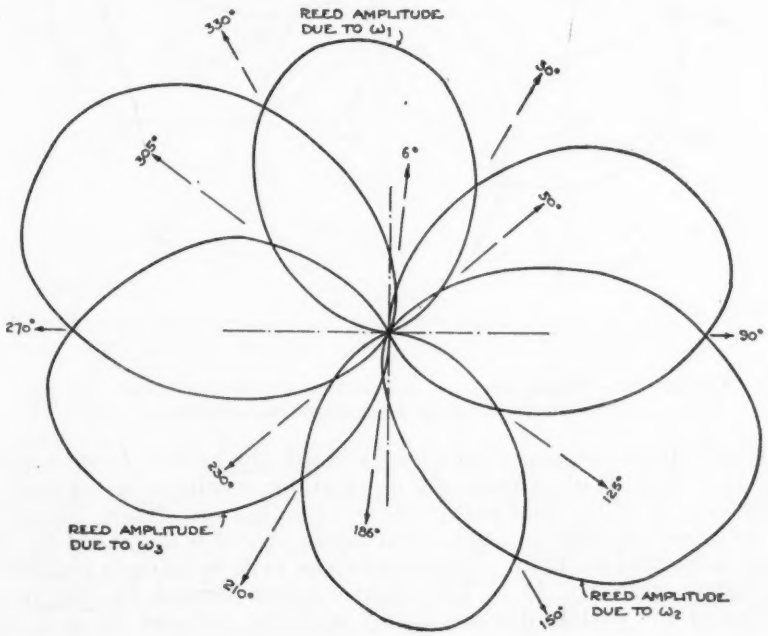

FIGURE 18.—*Received pattern corresponding to space pattern of Figure 17*

III. METHODS OF SHIFTING THE BEACON COURSES

The same means are available for shifting the beacon courses from their 30° space relationship (in order to align them with the airways emanating from a given airport) as have been previously described for application to the 4-course radio range.[5] A simpler method, applicable only to the 12-course beacon is, however, preferable. This method consists of displacing the stator windings from their normal 120° positions, and may be used when either audio-frequency grid bias switching or radio-frequency switching is employed.

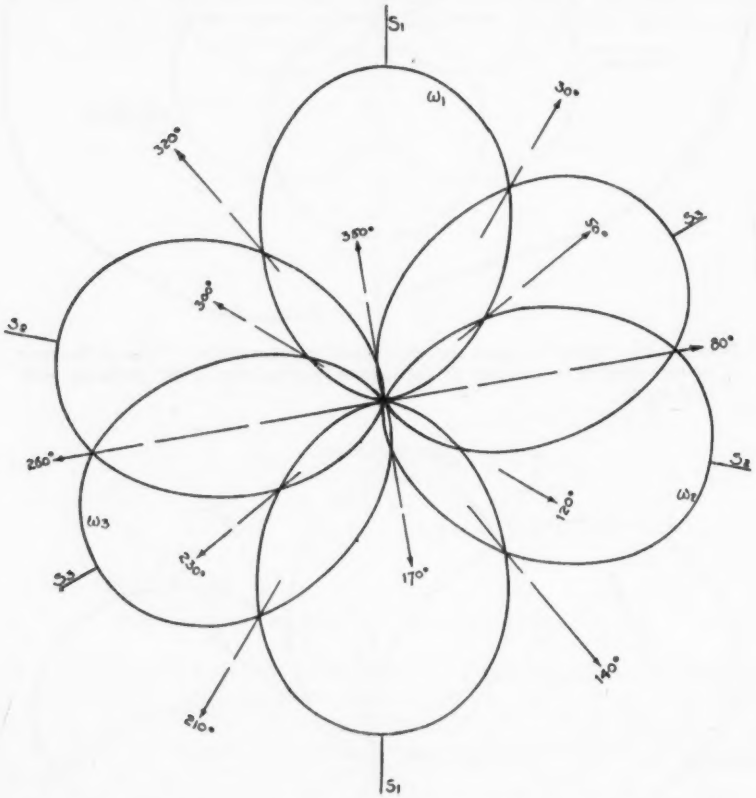

FIGURE 19.—*Displacement of beacon courses obtained when shifting stator No. 2 by 20° from its normal position*

When audio-frequency switching is used, the stators being excited one at a time, displacement of a given stator results in an equivalent displacement of the field pattern due to that stator. Thus, Figure 19 is the received polar pattern when stator No. 2 is displaced by 20° from its normal position. The pattern due to S_2 is similarly displaced. (Compare with fig. 11.) The eight courses formed by the intersection of the pattern due to stator S_2 with the patterns due to S_1 and

[5] H. Diamond, Applying the Visual Double-Modulation Type Radio Range to the Airways, B. S. Jour. Research.

S_3 are all shifted by 10° in the direction of displacement of S_2, while the four courses due to the patterns of S_1 and S_3 remain fixed in their normal positions. A greater variation of the angles between courses may be obtained by displacing two of the three stators in equal amounts, but in opposite directions. Figure 20 corresponds to a case of this kind, S_2 and S_3 being separated from S_1 by 130° instead of the normal value of 120°. The four courses formed by the intersection of the patterns due to S_1 and S_2 are here rotated 5° clockwise.

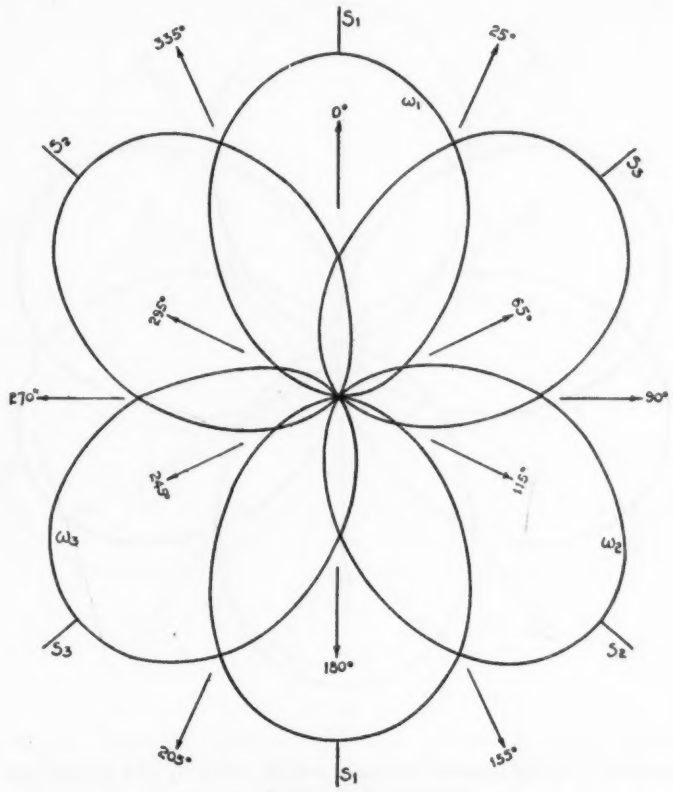

FIGURE 20.—*Displacement of beacon courses when S_2 and S_3 are separated by 130° from S_1 instead of the normal value of 120°*

The four courses due to the patterns of S_1 and S_3 are rotated 5° counter clockwise, while the four courses due to S_2 and S_3 remain fixed. Figure 21 is for the case when S_2 and S_3 are separated from S_1 by 110°. In this case the four courses due to S_1 and S_2 are rotated 5° counterclockwise, the four courses due to S_1 and S_3 are rotated 5° clockwise, and the four courses due to S_2 and S_3 again remain fixed. Because of the change in direction of rotation the angles between courses are quite different from those obtained in Figure 20. Note also that the majority of the courses are somewhat more useful in so far as signal strength and sharpness of course are concerned.

Using this method of attack it becomes possible to align the beacon courses with the airways at a great number of airports. In certain special cases, however, it may become necessary to resort to the other methods of course shifting described in the previous paper.[6]

In the system using radio-frequency switching of power, the fact that displacing the stators from their normal position serves to dis-

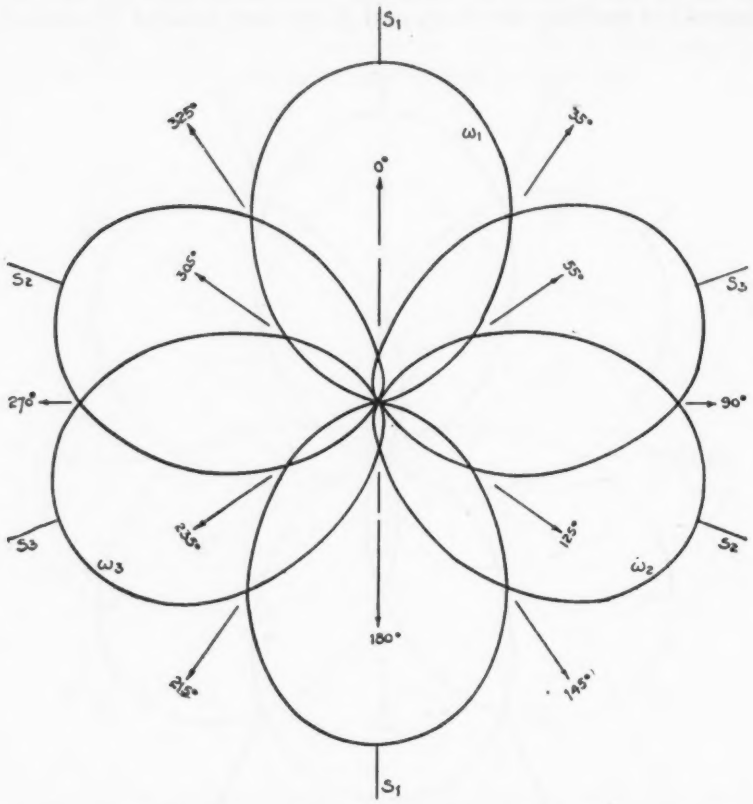

FIGURE 21.—*Displacement of beacon courses when S_2 and S_3 are separated by 110° from S_1*

tort the carrier renders this method of course shifting a little less powerful. Figure 22 is for the case when S_2 and S_3 are separated from S_1 by 110°. Note that the variation of the courses from their normal positions is not exactly the same as for Figure 21. Enough variation can be obtained with this method, however, to meet the requirements at most airports.

[6] See footnote 5, p. 366.

IV. TESTS

Numerous test flights have been made on the 12-course beacon described above. The distances obtainable on all 12 courses have been determined. Under average daytime conditions a distance of 100 miles on the weak courses and a correspondingly greater range on the strong courses is obtained. Ground tests were made at Media, Pa., 105 miles from College Park, Md., all 12 courses being

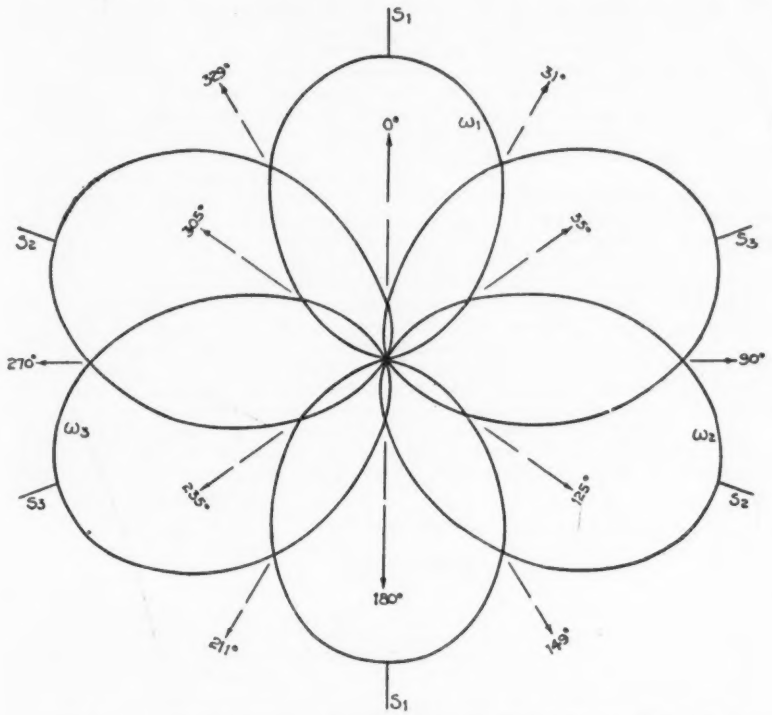

FIGURE 22.—*Stator positions are the same as for Figure 21 except that radio-frequency rather than audio-frequency switching is employed*

oriented through that point by rotating the goniometer at the beacon station and the angles between the courses thus determined. These tests were repeated at a later date, the same results being obtained. These results checked also the data on the angles between courses as obtained in the air.

WASHINGTON, September 18, 1929.

APPLYING THE RADIO RANGE TO THE AIRWAYS

By F. G. Kear and W. E. Jackson

ABSTRACT

In pursuance of the program of radio aids to flight undertaken by the Department of Commerce, design and installation work has progressed under the direction of the chief engineer, airways division, in the application of the radio range (directive radiobeacon) along the airways. To date, only the aural type has been put into routine daily operation, and it is the only type of beacon considered in this paper which discusses methods of adjusting the space pattern of the beacon system in order that the courses may align with the fixed airways. These beacons also need to be readily distinguished from one another and so designed that a minimum of interference is met.

By using a vertical wire antenna in addition to the loop antennas, and varying the relative power in the two loop antennas, it was found possible to secure practically any array of courses desired. The radio ranges at Hadley Field, N. J., and Bellefonte, Pa., were employed in the experimental work with excellent results. The field intensity measurements made gave space patterns which checked very well with the theoretical patterns for such antenna systems.

Careful spacing of the radio range within the frequency band, as well as distinctive coding of each beacon, solved the problem of interference.

In selecting the proper coding for the beacons a study of the physiological effects of various sound groups was made, and the final coding chosen was such as to give a signal of equal time duration on each side of the course. The signals still interlock to give the customary long dash when on the course.

The technique of applying those modifications was developed to the point where the adjustments could be made by the installation crew in the field without the aid of an engineer.

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I. INTRODUCTION

The aural type of the radio range [1] was installed by the airways division at Hadley Field, N. J., Bellefonte, Pa., and Cleveland, Ohio, in 1927 and 1928. After the first tests, it became necessary to adjust the beacon system in order to make the courses provided coincide with the fixed airways. The original aural type radio range established an equisignal zone of about 3° width extending in a straight line through the beacon approximately 100 miles either way. Another equisignal zone, at right angles thereto, approximately 12° in width, was also present, but on account of its excessive width was not usable. An airway extending 200 miles in a straight line with a field at its center is a situation seldom encountered. The use of

[1] F. H. Engel and F. W. Dunmore, A Directive Type of Radiobeacon and its Application to Navigation, B. S. S. Papers No. 480; January, 1924. Murphy and Wolfe, Stationary and Rotating Equisignal Beacons, J. S. A. E., **19**, 209; September, 1926. Dellinger and Pratt, Development of Radio Aids to Air Navigation, Proc. I. R. E., **16**, pp. 890-920; July, 1928.

lower power beacons at more frequent intervals, and between fields, might solve this difficulty, but would raise problems of interference and economy. In the actual use of the beacons along the airways the following problems had to be solved:

(*a*) Interference had to be kept to a minimum in order to prevent confusion.

(*b*) The course outlined had to be easily recognizable so that a slight deviation might be noticed.

(*c*) Radio ranges had to be so designed that they could be located at bends in the airway route; that is, the course given by the beacon must not be a straight line through the beacon, but an obtuse angle of controllable magnitude. Furthermore, both legs of the angle must be capable of simultaneous operation in order to accommodate increasing air traffic.

(*d*) Finally, it was necessary to service more than one course from a single radio range, a further development of the previous idea. Terminals in larger cities have many air routes entering, and each of these routes should be outlined by a beacon course. Since it would not be economically possible to install a separate beacon for each route the system had to be modified to accommodate multiple routes.

These conditions have all been satisfied on the radio range system as now in use on the airways, if the number of courses to be served does not exceed four. The purpose of this paper is to give a detailed account of the means employed to meet these conditions.

II. INTERFERENCE BETWEEN RADIO RANGES

Two methods have been successfully adopted to differentiate between radio ranges. The first method was to allocate different frequencies in the band from 285 to 350 kc. to each radio range. Particular care was taken to separate adjacent beacon frequencies by at least 12 kc. When utilizing the ordinary aircraft receiver using two stages of shield grid tube, radio-frequency amplification, detector and two stages audio with a 6-foot rod antenna, it was possible to tune in either a beacon 100 miles ahead or 100 miles behind, when both were operating simultaneously on frequencies separated by 8 kc. The average power output from a beacon installation is 2 kw.

The second method used to eliminate possible confusion between radio ranges was to establish a system of distinctive code signals. The signals of necessity had to be such that they interlocked and gave the resulting long dash when on the course. The first group of signals adopted were (— . and . —); (— . — and . .); (— . . — and . . .); and (— — — and . .); two characteristic signals being required for each interlocking radio range. Results showed that radio ranges using the — . and . — characteristics gave very distinctive courses. However, when the characters — . — and . . were used as interlocking signals, a peculiar physiological effect was observed. Tests indicated that the course was apparently bent slightly in an S shape. In reality, field strength measurements proved the course to be straight. When close to the range and on the course as indicated by field-intensity measurement, the character — . — would apparently predominate, causing the pilot to bear toward the . . side of the course. When at approximately 100 miles from the range, tests indicated that the . . character would predominate while on the course, thus causing the

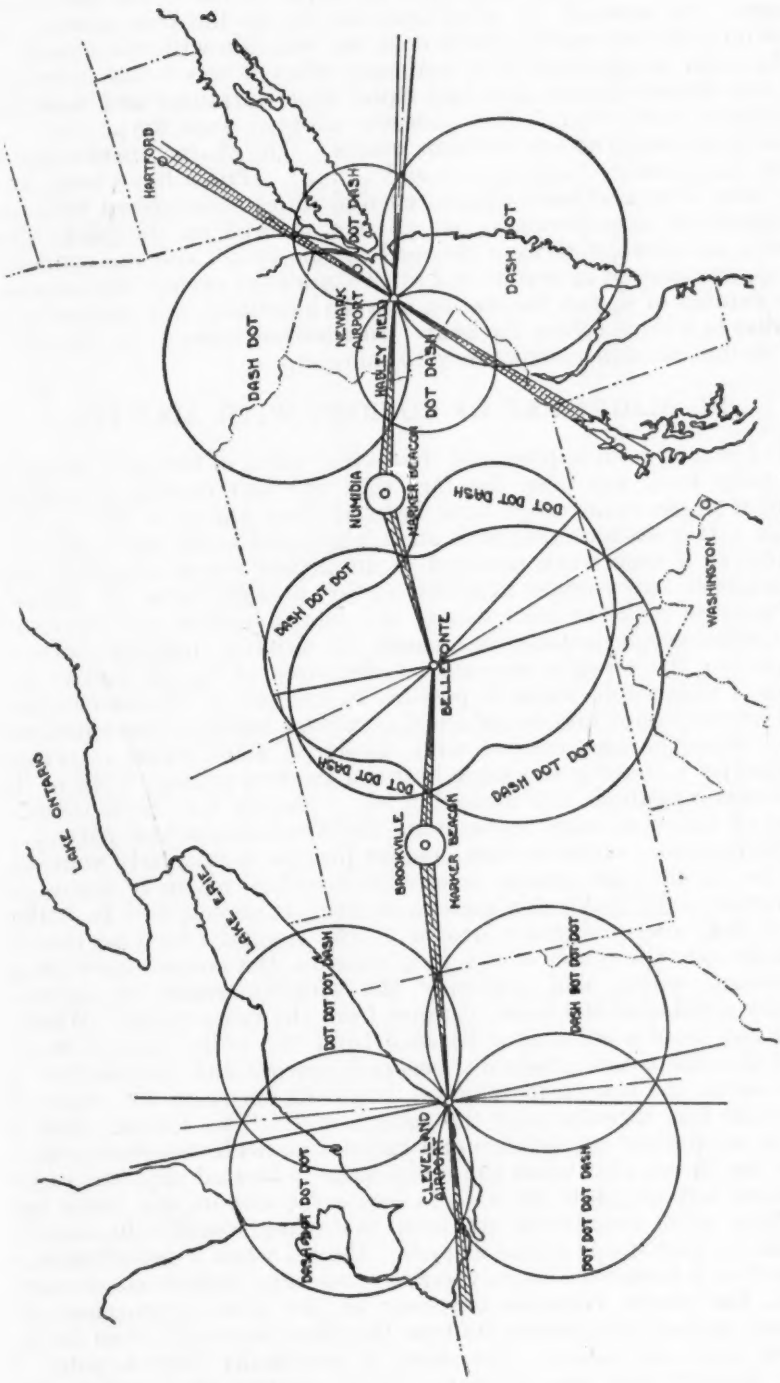

FIGURE 1.—*Air route, Cleveland to New York*

pilot to compensate for this effect by flying on the _ . _ side of the course. As a result the pilot does not fly on the true course, but flies on a curved course which does not coincide with the airway.

In order to eliminate this confusing effect it was found necessary to use characteristics that had equal time durations and were the inverse of each other. This plan was adopted since the _ . and . _ were found to give such excellent results. The characteristics chosen were (_ . . and . . _); (_ . . . and . . . _). These have been used for some time and have eliminated difficulties encountered with dissymmetrical arrangements, but are not favored by the pilot. Recently the airways division changed signals to _ . and . _ combinations, transmitted in groups of 2 to 12 signals per cycle. By counting the number of signals the station may be identified, this system being similar to a clock tolling the hour. In addition, beacons are identified by station announcement every 15 minutes.

III. ALIGNMENT OF COURSES WITH AIRWAYS

It has long been appreciated that a limitation of the radio range in its early form has been the fact that the four courses emanating from a single radio range have been at fixed angles of 90° to each other. It is obvious that such an arrangement could serve only one course at a time when situated at an airport except where by rare coincidence two courses extended at 90° or 180° from an airport. In order to make at least two of the four available courses useful the radiobeacon installations could be situated halfway between points on the straight airways at distances of approximately 200 miles. This would make it possible to use two of the four courses and at the same time to reduce the angular width of the equisignal zone since the two courses were displaced 180°. This is accomplished by increasing the angle between the two primary coils of the goniometer to about 120° instead of 90°. (See fig. 4.) Some installations of this type were made along the Transcontinental Airway.

Placing radio ranges in this manner has one particularly annoying feature in that the course is usually broadest where it should be narrowest. To make this statement clear, it should first be understood that an equisignal course is a true angular function; that is, directly over the center of the loop antenna the courses have an infinitesimal width, and gradually the width increases to approximately 6 miles at 100 miles distance from the radio range. When a pilot flies from a point at a distance from the radio range it is evident that his course gradually becomes sharper and narrower as he approaches the beacon installation, and if he keeps on his course it will take him directly over the radio tower. This feature alone is one of paramount importance and can not be neglected, since experience has shown that when the radio range is located adjacent to the terminal airport pilots are able to locate the airport and make safe landings when conditions are such that they would otherwise be unable to find the terminal airport. Hence, when a radiobeacon is located at a terminal airport there are two very distinct advantages: First, the course becomes narrower as the pilot approached the beacon; second, the beacon informs the pilot definitely when he has passed over the tower. Therefore, it practically fixes a point in space directly over the antennas. It is apparent that such a point

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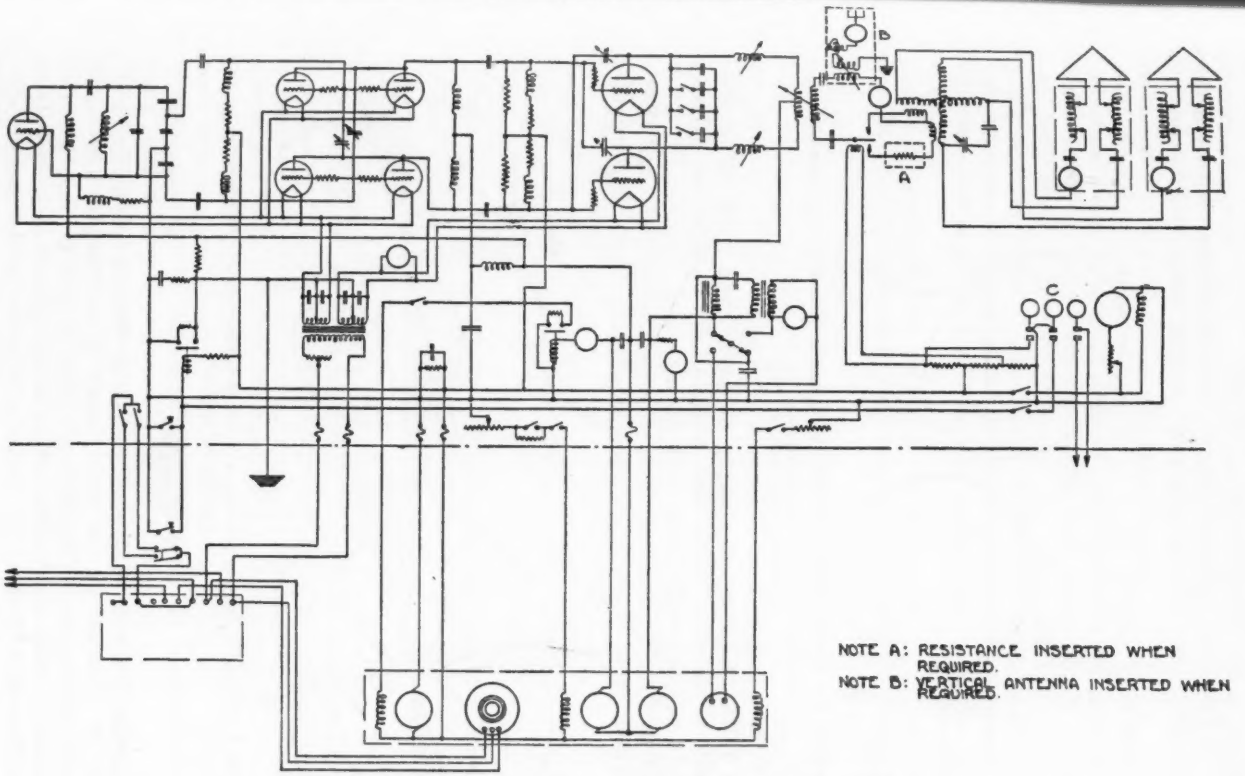

FIGURE 2.—*Schematic diagram of typical radio range*

The master oscillator is a 50-watt tube employing the Colpitts circuit. This is amplified by a set of four 50-watt tubes operating in a push-pull circuit and cross-neutralized. The final power amplifier contains two 1-kw tubes of which the plate circuit is tuned.

The tuned plate circuit is coupled by an untuned link circuit to the goniometer primaries and keying is accomplished at this point. The keying cams are shown at *C*. One cam controls the input power and another connects the primaries of the goniometer alternately to the circuit.

The resistance at *A* permits shifting the 90° courses as desired and the vertical wire antenna shown at *B* introduces the shift of the 180° courses. Either or both may be employed as desired.

in space would be of unquestionable value if located adjacent to a terminal airport instead of halfway between two airports. It was with these particular features in mind that the problem of fitting radio ranges to the airways was attacked.

Two fundamental schemes have been developed which permit the use of two fixed courses displaced at any angle varying between

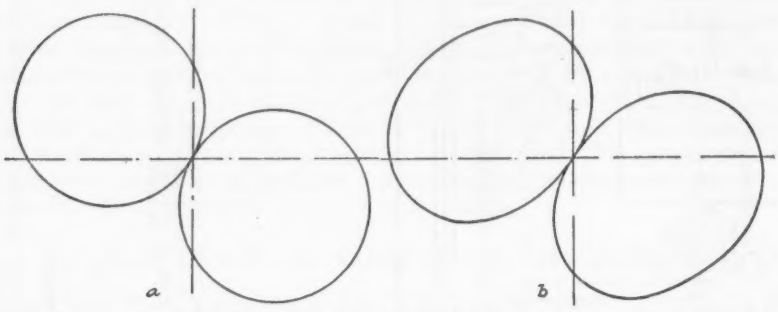

FIGURE 3.—*Field intensity pattern of a single phantom loop antenna*

(*a*) Theoretical.
(*b*) Observed.

45° and 180°. Courses emanating at angles less than 45° can not practically be serviced with one installation, because an excessive decrease in power results from such an attempt.

Method used for courses emanating at angles between 45° and 135°.—The method used to serve courses emanating from an airport at

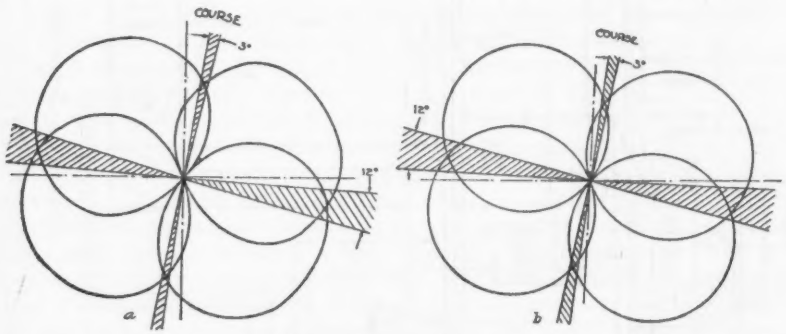

FIGURE 4.—*Field intensity pattern of typical radio range. Goniometer primaries set at 120°*

(*a*) Theoretical.
(*b*) Observed.

angles varying between 45° and 135° is as follows: A noninductive resistance is inserted in the link circuit in series with one of the goniometer primaries. This reduces the power in one phantom loop antenna [2] while the power in the other phantom loop antenna is left unaffected. By varying the ratio of power in the two phantom

[2] A phantom loop antenna is the resultant figure-of-eight space pattern occurring when both loop antennas are coupled to one goniometer primary. One phanton loop antenna exists in space for each goniometer primary. The angular relation of the phantom loop antennas is the same as that of the goniometer primaries. For a further treatment of this subject see Murphy and Wolfe, Stationary and Rotating Equisignal Beacons, J. Soc. of Automotive Engs., **19**, p. 209, September, 1926.

loop antennas by means of resistance the courses may be made to shift from their normal 90° displacement to any angle between 45° and 135°. (See fig. 5.) It should be carefully noted that this variation depends upon several variables, including loop antenna resistance, mutual inductance between primary and secondary of goniometer, and power factor of link circuit. These should be taken care of jointly in each particular installation.

Method used for courses emanating at angles between 135° and 180°.—The normal polar pattern of crossed loop antennas is a pair of figures-of-eight at 90°. This gives four equisignal zones which are referred to as "courses" in beacon terminology. (See fig. 6.) In order to increase the sharpness of the course the goniometer primaries are frequently set at 120° instead of 90°. This gives four courses, two of which are about 3° wide, while the remaining two are 12° wide. (See fig. 4.)

If a vertical wire is now permitted to radiate in time phase with the radiation from the phantom loop antenna the field intensity pattern

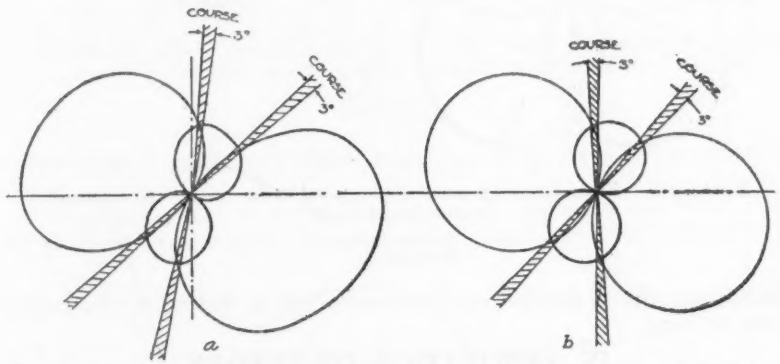

FIGURE 5.—*Field intensity pattern of radio range with resistance inserted in series with one goniometer primary. Primaries set at 90°*

(*a*) Observed.
(*b*) Theoretical.

will be distorted as shown in Figures 7 and 8. It will be noted that two lobes diminish and two increase. This changes the relative position of the equisignal zones so that the course approaching the beacon is no longer 180° from the one leaving. The amount of this shift may be controlled by adjusting the magnitude of the current in the vertical wire. This shift is limited only by the disappearance of two of the lobes [3] forming two cardioid patterns at right angles, thus giving two equisignal zones displaced 180° instead of four displaced at various angles.

It has previously been mentioned that in the original beacon system the goniometer primaries were set at an angle of 120° to secure a narrow course. When means are employed to bend the course this is not advisable. There is danger of one lobe shrinking so far that it intersects the adjacent lobe on the wrong portion of its contour. This will be apparent from Figure 9. Four courses are present so far as the ear can detect, but as the lobe decreases the course will no

[3] E. Z. Stowell, A Unidirectional Radiobeacon for Aircraft, B. S. Jour. of Research; December, 1928.

longer shift properly. Furthermore, the course at this intersection is not sharp enough to be used. In order to prevent this in beacon

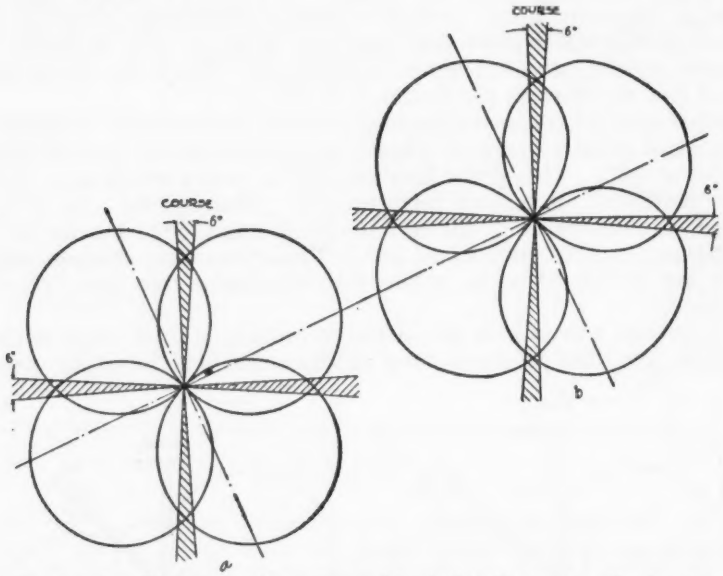

FIGURE 6.—*Field intensity pattern of typical radio range. Goniometer primaries set at 90°*

(*a*) Theoretical.
(*b*) Observed.

installations the primaries are frequently set at 90° when the courses are to be bent.

IV. APPLICATION OF THEORY

Having decided upon a method for aligning the courses of the radio range with the airways, the next problem was to develop a means of

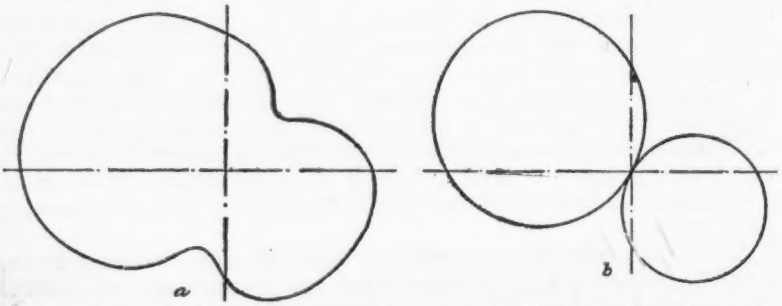

FIGURE 7.—*Field intensity pattern of one phantom loop antenna and vertical antenna energized simultaneously*

(*a*) Observed.
(*b*) Theoretical.

applying it to the beacon installations. The radio ranges at Hadley Field, New Brunswick, N. J., and Bellefonte, Pa., were selected for these tests.

The airway route through Bellefonte has a 14° bend at Bellefonte and, consequently, the antenna effect method was employed.

A vertical wire antenna was installed on the radio range tower and this was tuned to resonance by a suitable series inductance. The

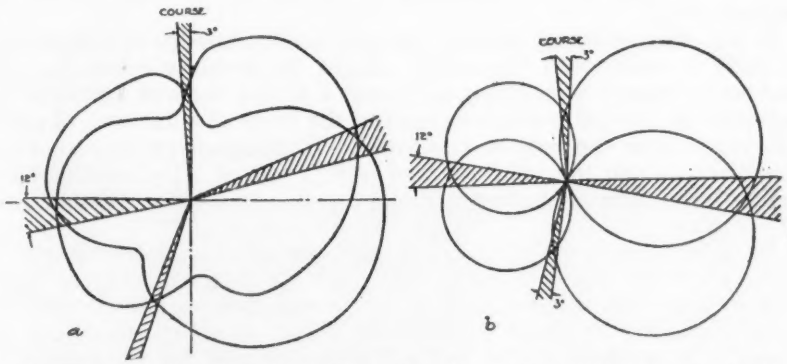

FIGURE 8.—*Field intensity pattern of radio range employing a vertical antenna in addition to the loops. Goniometer primaries set at 120°*

(a) Observed.
(b) Theoretical.

circuit was of sufficiently high resistance to have a broad resonance curve.

The antenna was at first excited by coupling it to the master oscillator. The results from this were poor, and analysis showed that a

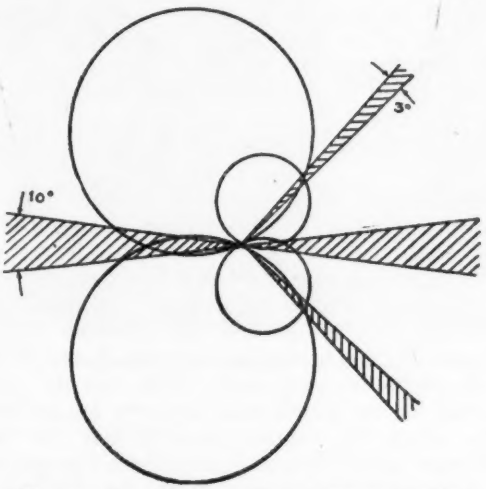

FIGURE 9.—*Field pattern of Figure 8 with incorrect time phase of vertical antenna*

pronounced phase shift occurred between the master oscillator and the goniometer, due to the particular coupling circuits employed. To eliminate this, a coupling coil was inserted in the common goniometer primary circuit, and the antenna coupled to this. This resulted in excellent control of the amount of shift, displacements of 28° being

readily obtainable. The goniometer primaries were set at 90° for this work.

The final adjustment was made by controlling the degree of the antenna coupling. It is necessary that the antenna be in tune to prevent dephasing; consequently, detuning will not accomplish the desired result.

It was also necessary to have an accurate knowledge of the amount of shift in order that the course might be properly oriented. For first adjustments a receiving set using a 6-foot vertical antenna was mounted in a truck and driven around the loops at a distance of about 100 yards from the base of the tower. Readings were very sharp at this distance and the 14° bend was easily checked. By locating landmarks from compass bearings it was possible to align the course with the airways.

In order to secure the observed field intensity patterns shown the same receiving set was employed with its vertical pole antenna. The output was connected to a calibrated thermoelement and the signal intensity adjusted to keep the tubes under saturation at all times. In employing the vertical wire antenna for distorting the pattern the receiving set was stationary and the goniometer rotated through 360°. With the series resistance method, the set was moved around the beacon tower.

Discrepancies between observed and theoretical patterns are due chiefly to phase shift between the loop antenna currents and the vertical wire antenna current.

For a further check the truck was taken to Snowshoe Junction to the west and to Aaronsburg to the east. (These are, respectively, 10 and 20 miles from the radio range.) The readings here checked with those taken at the beacon tower to within half a degree, which is well within the accuracy of measurement. As a final check, the course was flown over, and again the readings checked those taken at the beacon. From this and from data secured on later occasions, it was decided that an accuracy of 1° could be expected from measurements made at the beacon tower in spite of the predominating induction field.

Hadley Field, besides being the eastern terminus of the Transcontinental Airway, has two other air lines entering it. Hartford to the north, and Washington to the south, need to be served by the same radio range. Washington and Hartford lie in a straight line through Hadley Field, but the course to the west is not at 90° to these. This presented an opportunity to use the first method described, namely, that of inserting resistance in the link circuit of one of the goniometer primaries, which, as before explained, shifts the 90° courses.

With the current in one goniometer primary approximately one-half the value of the other, the courses were shifted the desired amount.

Here, also, it was found desirable to adjust the goniometer primaries to 90° in order that the courses might be of equal power. This change in relative field intensity of the two phantom loops has another very advantageous effect in that it sharpens the course to a considerable degree. By referring to Figure 5 it will be seen that since the intersection of the smaller figure-of-eight comes at the point of rapid change of the large figure-of-eight, the resulting course is quite sharp. By measurement the courses have been found to be approximately

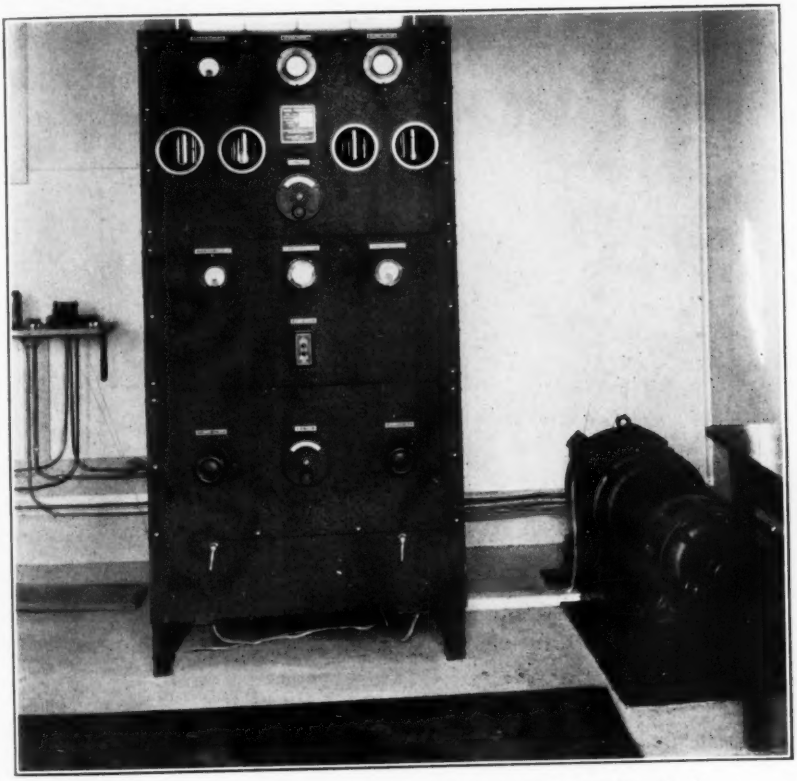

FIGURE 10.—*Radio range installation at Hadley Field, N. J.*

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3° wide. This is much sharper than the usual course resulting from a 90° separation of the goniometer primaries.

The courses were checked here in a manner similar to that used at Bellefonte.

One other modification of the system is possible. When using a vertical wire antenna it may be keyed by a relay in the same circuit as the one goniometer primary. The result of this will be to affect only one phantom loop and thus shift both the 90° and the 180° courses.

With these three means at hand it becomes a relatively simple matter to satisfy almost any requirement where the number of courses to be served does not exceed three, and also a great number of 4-course air terminals. The adjustments are not so critical as to be unstable and once made, remain indefinitely. Very little extra apparatus is required and the maintenance is not difficult. All the requirements for the aural type of radio range, as listed in the early part of this paper, are therefore fulfilled.

WASHINGTON, August 8, 1929.

NEW PIEZO OSCILLATIONS WITH QUARTZ CYLINDERS CUT ALONG THE OPTICAL AXIS

By August Hund and R. B. Wright

ABSTRACT

It is shown that oscillations of a new type can be produced, using a quartz cylinder cut along the optical axis. Some of the electrode mountings used were suggested by Röntgen's experimental work and the more recent work of Tawil. In order to produce these oscillations it was necessary to use new adaptations of regenerative circuits as the driving circuit.

These oscillations were studied experimentally through the medium of glow discharge patterns, a phemomenon of ionization produced by the quartz cylinder oscillating in a few millimeters of helium. They were studied theoretically by comparing the observed frequencies of oscillation with the computed values for the three different types or modes of vibration. Both studies indicate that these oscillations are of a true piezo-electric character.

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I. INTRODUCTION

In relation to crystalline quartz cylinders cut along the optical axis, E. P. Tawil [1] describes a new phenomenon, which he states to be different from piezo-electric phenomena, and suggests that it be called "strepho-electricity." In the description it is shown how opposite electrical charges appear, respectively, on the cylindrical surface and the ends when such a cylinder is subjected to a torsion about its cylindrical (and optical) axis. The charges thus produced appear to be proportional to the variation of the torsional strain. Moreover, the polarity of these charges reverses when the direction of torsion is reversed, and, in addition, the polarity is dependent upon the optical structure of the quartz, or, specifically, upon the optical rotation thereof.

In 1890, W. C. Röntgen,[2] experimenting with static torsional forces on this same type of quartz cylinder cut along the optical axis, found that a twist about this axis produces charges of opposite polarity in consecutive quadrants around the cylinder, as is indicated in Figure 1. A, B, C, D, E, and F denote points of neutrality around the cylinder (which is assumed perpendicular to the plane of the paper) when ordinary piezo-electric effects occur, whereas α, β, γ, and δ mark such points of zero surface charge on the envelope when tor-

[1] Nouveau mode de developpement d'électricité par torsion dans les cristaux de quartz. (New method of producing electricity by torsion on quartz crystals.) Comptes Rendus, 187, pp. 1042–1044; Dec. 3, 1928.
[2] Wied. Ann. d. Physik, 39, p. 16; 1890.

sional stresses are acting. Those polarities indicated in the figure within two concentric circles denote the charges developed by torsional stress, while those within the single circles refer to ordinary piezo-electric polarizations. A result such as indicated in this figure does not seem to be correct for quartz, considering its three piezo-electric axes, which should ordinarily lead one to expect six alternate charges around the cylinder. Röntgen himself doubted the outcome of his experiment somewhat and repeated it with the same result; a result which would be in direct contradiction to W. Voigt's theory if the cylinders used were accurately oriented.[3]

Both the above experiments dealt with *static* torsional forces. One of the purposes of this paper is to show that *dynamic* torsional forces can produce electric effects, and vice versa. A second purpose is the

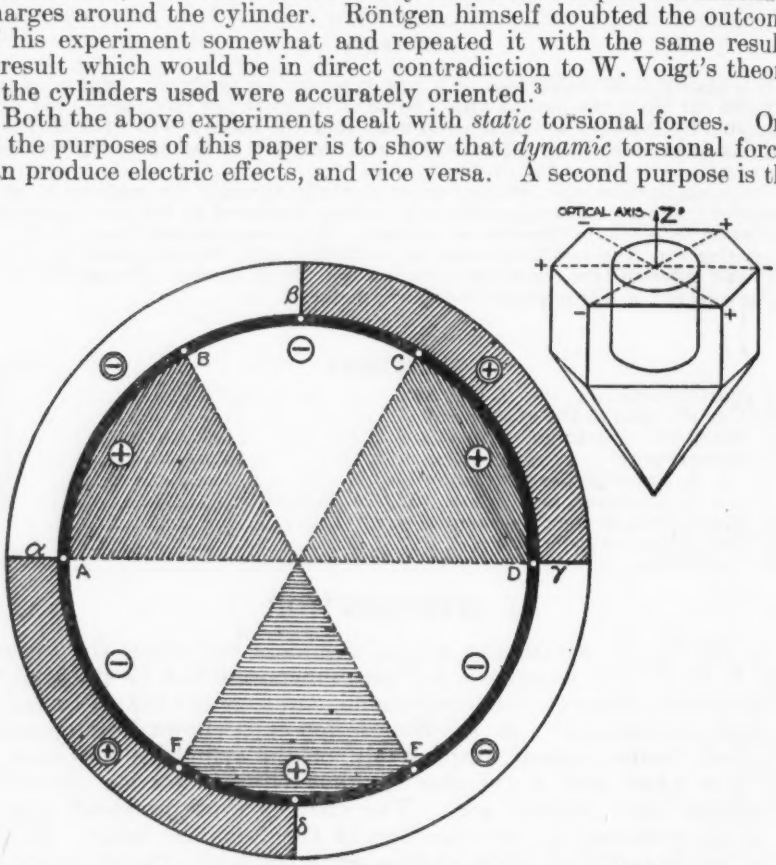


FIGURE 1.—*Charges on quartz cylinder (both when normal and when torsional strains exist)*

demonstration of new oscillations produced with crystals cut along the optical axis, which oscillations, incidentally, may be explained theoretically without conflicting with Voigt's theory. A third purpose of this paper is to show that these oscillations embody true piezo-electric action.

II. CIRCUITS USED IN THE EXPERIMENTS

Ordinary circuits [4] can not be used for producing oscillations of this type. This is due, no doubt, partially to the fact that the

[3] W. Voigt, Lehrbuch der Kristallphysik, pp. 879–891; see conclusions on p. 891.

[4] In which the piezo-electric element is connected either between the grid and the filament, or between the grid and the plate, and in which a condenser in parallel with a coil is employed in the anode branch. (For details, see Proc. I. R. E., **14,** pp. 447–469; August, 1926.)

modulus δ_{14} which has the value of only $+1.45\times10^{-8}$ cgs electrostatic units, is operative in the case of torsional oscillations, whereas the modulus responsible for the more usual "Curie cut" oscillations has the value $\delta_{11}=-6.45\times10^{-8}$ cgs electrostatic units.[5] It was therefore necessary to resort to circuits which are so regenerative that they are on the verge of self-oscillation. The arrangements *a*, *b*, *c*, and *d* of Figure 2 were found to work satisfactorily. In the systems *a* and *b* a small condenser C_o is employed for adjusting the feed-back. In the system *d* a small condenser may or may not be used across the piezo-electric element.

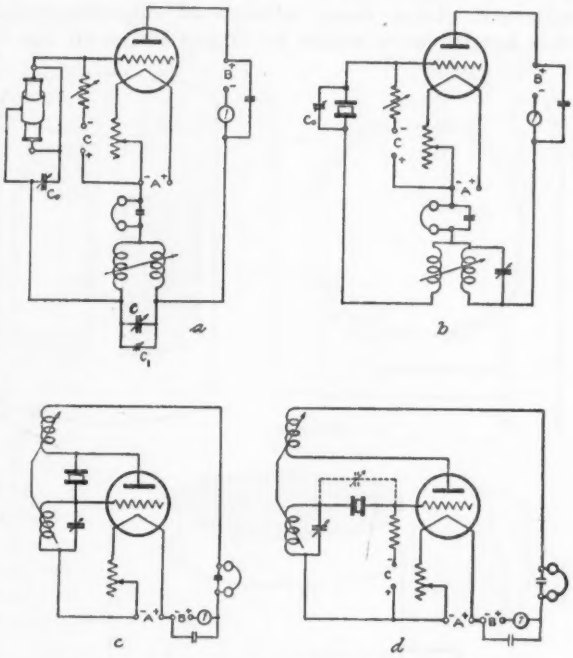


FIGURE 2.—*Driving circuits for oscillations*

III. ELECTRODE MOUNTINGS

The experiments by Röntgen as well as the recent investigation by Tawil suggest two mountings, shown in Figure 3, A and B, respectively. These will be referred to throughout the paper as mountings A and B. It is seen that mounting A consists of four electrodes placed around the cylinder, of which alternate ones are of the same polarity, while for mounting B a cylindrical electrode acts with respect to the two end electrodes which are in parallel.

Other mountings with which oscillations were obtained are indicated in Figures 4 and 23. Mounting C consists of three electrodes properly located with respect to the three piezo-electric axes, connected in parallel to form one terminal, while the other terminal is formed by the two end disks in parallel.

Mounting D consists of two sets of three electrodes each. One set connects to the upper end disk, and the other to the lower disk. The electrodes of the upper set, like those of the lower set, are spaced 120° apart around the cylinder, one set having an angular displacement of 60° with respect to the other.

[5] Here each of the three different types or modes of vibration, including both their respective fundamentals and modes of higher frequency, must be distinguished from the other two. The three different types or modes of vibration referred to are: (1) longitudinal vibration, (2) transverse or bending vibration, and (3) torsional vibrations. This paper describes the first-known successful attempt to produce torsional vibrations along the optical axis.

Mounting E consists of six metal strips around the cylinder, alternate ones being interconnected. No end disks were used in this case. This electrode system corresponds closely to the piezo-electric structure of the cylinder.

Mounting F consists of three rings around the cylinder, the two end ones being opposite in polarity to the central one.

Mounting G (see fig. 23) consists of six strips around the upper portion of the cylinder and six strips around the lower portion, adjacent strips being always of opposite polarity. Mountings of this nature were made by fixing strips to the inside of a glass tube which was placed around the quartz cylinder.

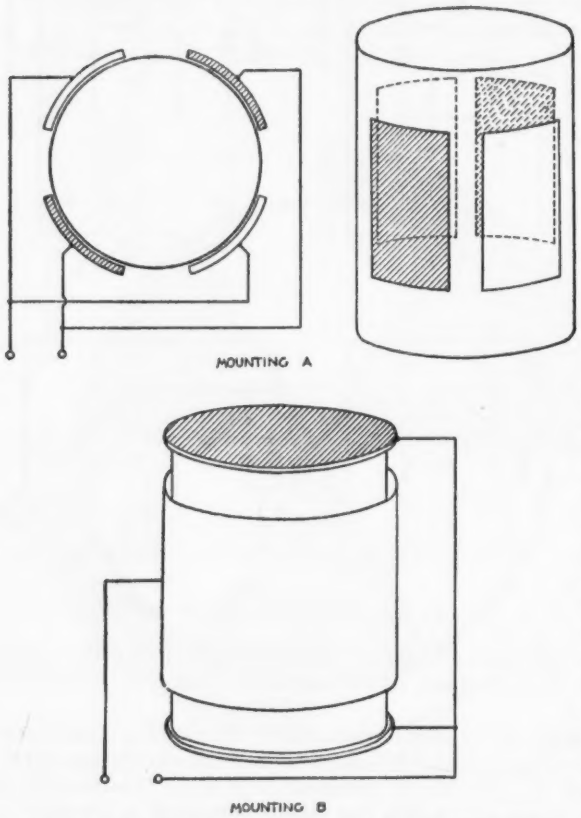


FIGURE 3.—*Electrode mountings for new ocillations*

IV. EXPERIMENTAL

1. EXPERIMENTS WITH MOUNTING B

For studying different modes of vibration, either the dust method by Kundt,[6] or the glow discharge method used by Giebe and Scheibe[7] are convenient means. Since the glow-discharge method has advantages over Kundt's procedure, it was used.

Glow discharges under a gas pressure of several millimeters of mercury were produced in neon, in helium, in a mixture of both, and in nitrogen, but most of the photographs shown here were of the quartz cylinder oscillating in helium.

When using mounting B the upper disk was omitted in order that the end pattern might be observed. This mounting, as well as

[6] A. Kundt, Über eine einfache Methode zur Untersuchung der Thermo-Elektricität und Piezo-Elektricität der Krystalle. (On a simple method for the investigation of thermoelectricity and piezoelectricity of crystals.) Berlin Akademie, **16**, p. 421; 1883.

[7] E. Giebe and A. Scheibe, Sichtbarmachung von hochfrequenten Longitudinalschwingungen piezoelektricher Kristallstäbe. (Luminous effects of high frequency longitudinal vibrations of piezo-electric crystals.) Z. f. Phys., **33**, p. 335, 1925; and Elektrotechnische Nachrichtechnik, **5**, pp. 65-82, February, 1928.

all others, consisted of electrodes of aluminum. In this way the sputtering of the crystal was avoided. The air gap between the crystal and the cylindrical electrode of mounting B was about 1 mm.

Figure 5 shows a cylinder in oscillation, with discharge effects along the optical axis. On pursuing the study of this type of discharge, it was found that for a higher gas pressure (and, incidentally, with a cylindrical cut crystal whose height was slightly less than the one shown in fig. 5) a small spherical discharge appeared, rising some distance above the crystal as shown in Figure 6. The crystal oscillation for this case produced a steady alternating current of 118 kc. With the same cylinder an axial glow, similar to that shown in Figure 5, appeared at a frequency of 179 kc. By properly adjusting the voltage of the oscillation by means of the feed-back, however, the various patterns, *a*, *b*, *c*, and *d* shown in Figure 7 could be produced. As may be readily understood by a comparison of the photographs with the diagrams which accompany them, it was difficult to get faithful photographic reproductions. In many cases the patterns as they appeared to the eye, consisted of designs beautiful in their detail. Four of these cases are to be found in Figure 7. The pattern shown in Figure 7 (*a*) looked like a small equilateral triangle with a circular glow inside. The dotted portions indicate discharges from the pattern over the surface toward the cylindrical electrode. In Figure 7 (*b*) only a triangular glow appeared, whereas in (*c*) a triangular glow appeared in the center with three circular glows, spaced 120° around the end face of the cylinder. For these discharge patterns and all the others, the dotted lines indicate discharge between surface-charge patterns or between surface-charge patterns and the electrode or electrodes around the cylinder.

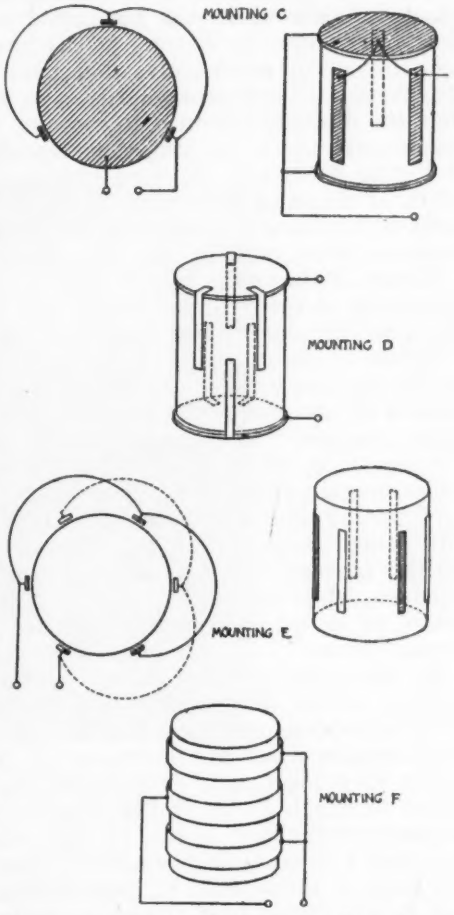


FIGURE 4.—*Other electrode mountings for new oscillations*

Generally speaking, the 179 kc oscillation (fig. 7) was always characterized by a triangular pattern, whereas to the 118 kc oscillation of Figure 6 there always corresponded a circular pattern at the center.

The same cylinder oscillated also at 288 kc, with a discharge pattern as shown in Figure 8. It will be noted that two diametrically located large circular glow discharges were accompanied by four small discharge points *a*, *b*, *c*, and *d* spaced evenly around the envelope of the cylinder, completing in a way the hexagonal formation which one would expect on account of the three piezo-electric axes.

Figure 9 (*a*) shows three circular surface discharges on the top of the crystal, which were located at the corners of an equilateral triangle. There were also six circular surface discharges around the cylinder which indicate again the hexagonal structure of the quartz. The discharges from the corners of the hexagon to those of the triangle probably occur alternately, since points *b* and *c*, as shown in the figure, must be of opposite polarity. In other words, it is very probable that the discharge from *a* to *b* occurs during one half cycle and the discharge from *a* to *c* during the succeeding one. The patterns shown in Figure 9 (*a*) and (*b*) were obtained with the same cylinder oscillating at the same frequency in helium. The difference in the patterns is due to a difference in the pressure of the helium gas, a lower pressure being used in the case of Figure 9 (*b*).

Figure 10 shows the case of a 301 kc oscillation. The piezo-electric symmetry of the cylinder can in this case be interpreted only from the three circular surface discharges on the top face.

Figure 11 shows a pattern for which the circular surface discharges on the top face were at the corners of two equilateral triangles. The corners of the smaller triangle were the mid-points of the sides of the larger triangle. In addition, around the cylindrical envelope, near the top face, three more surface discharges were visible. They indicate again part of the hexagonal structure of the quartz.

Figure 12 indicates most strikingly the piezo-electric nature of this class of oscillations. The circular surface discharges accompanying this frequency of oscillation appear around the envelope near the top face, while for the case of the 296 kc oscillation they are to be found, as shown in Figure 13, on the top face, somewhat inside the circumference.

At this point it was deemed important to find out whether those circular surface discharges which appear on top, or those appearing around the envelope, mark the three piezo-electric axes of the crystal. To determine this it was first necessary to locate these axes. With this end in view the quartz cylinder was suspended between two parallel plates to which 20 kv (taken from a d. c. source) was applied. In an electrostatic field of this strength the crystal readily turned itself into such a position that one of the three piezo-electric axes was along the lines of force; that is, perpendicular to the plates. From this test it was found that the glow discharge of the 331 kc oscillation (fig. 12) marked exactly the piezo-electric axes of the cylinder, while the six surface discharges of Figure 13 appeared halfway between these axes, as is indicated in the figure.

Another interesting glow discharge occurred with a 262 kc oscillation, shown in Figure 14. Again we find six discharge spots on the top face which produced six space discharges, which in turn ran together, forming a discharge ring somewhat above the cylinder. From the ring-shaped discharge six space discharges ran radially outward and then down the cylinder toward the cylindrical metal electrode.

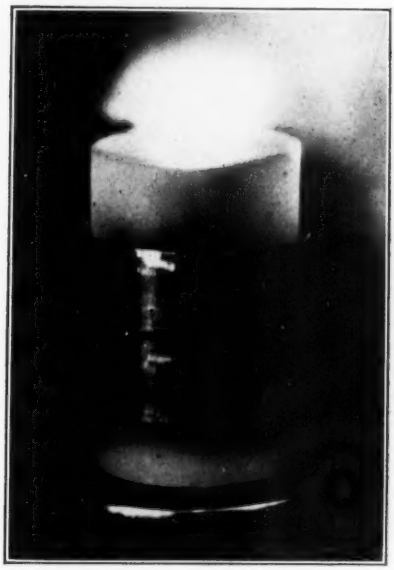
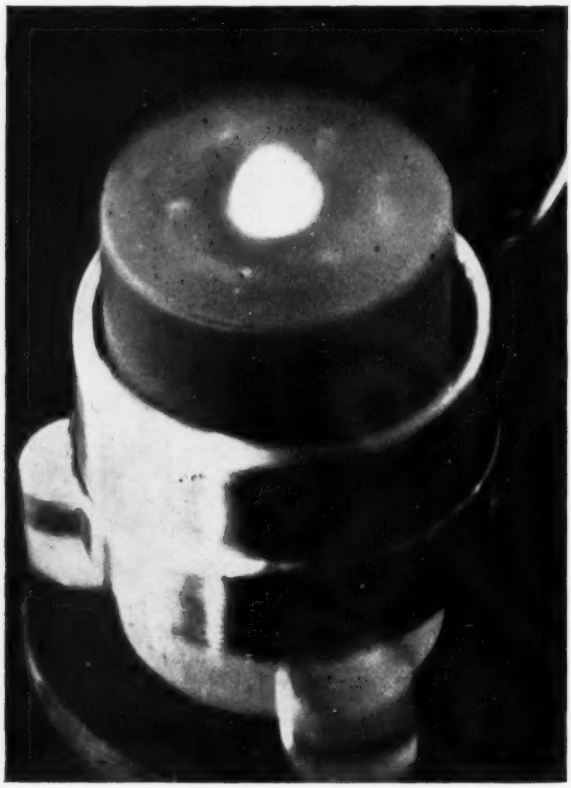


FIGURE 5.—*186 kc, mounting B, height 38.3 mm, diameter 24.715 mm*



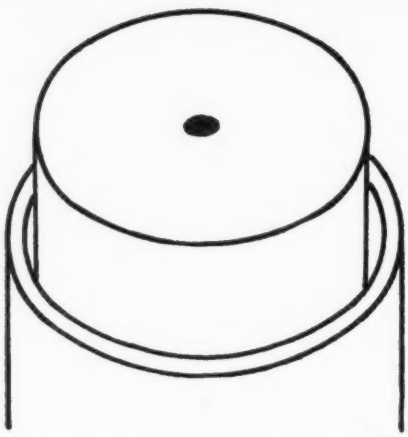


FIGURE 6.—*118 kc, mounting B, height 36.67 mm, diameter 24.715 mm*

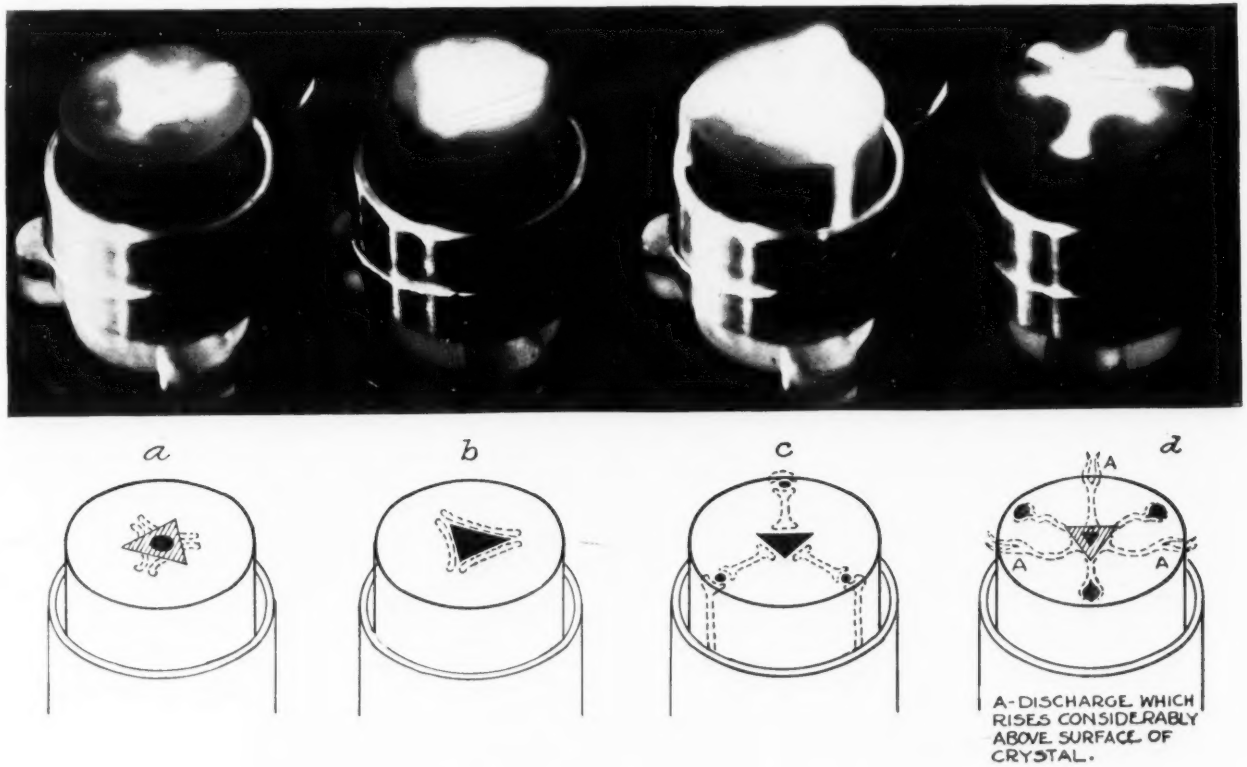


FIGURE 7.—*179 kc, mounting B, height 36.67 mm, diameter 24.715 mm*

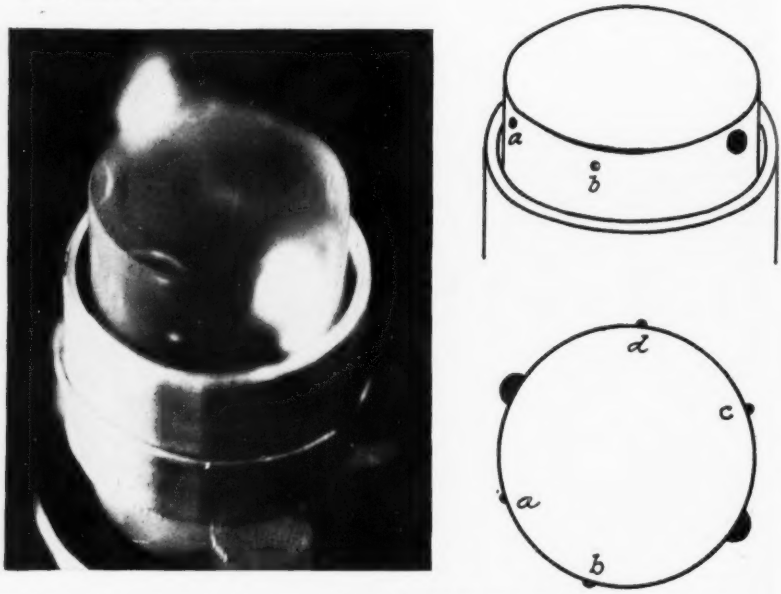


FIGURE 8.—*288 kc, mounting B, height 36.67 mm, diameter 24.715 mm*

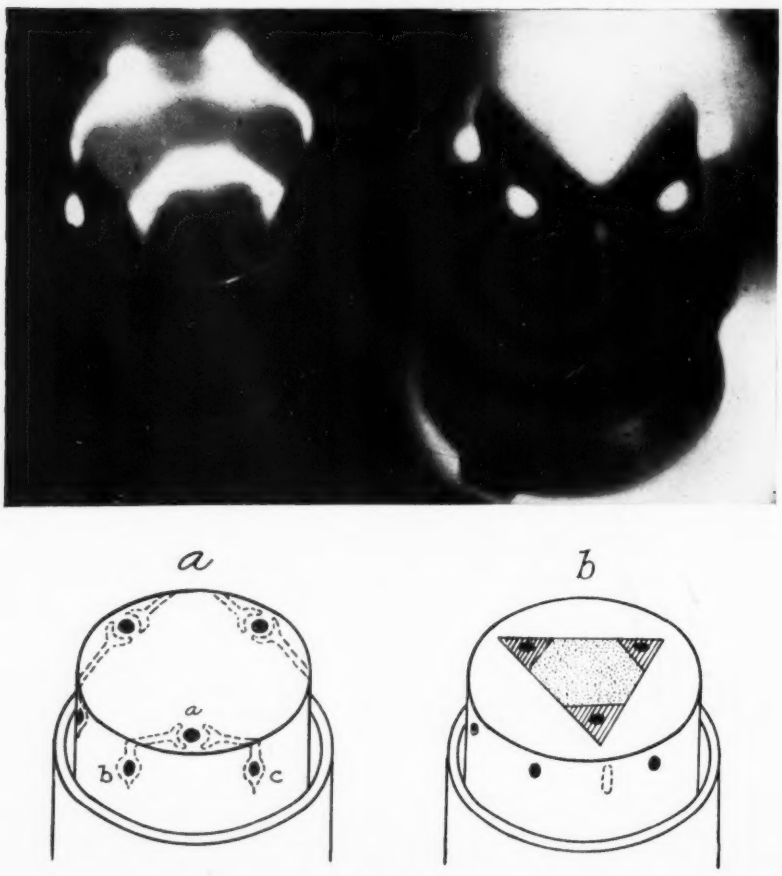
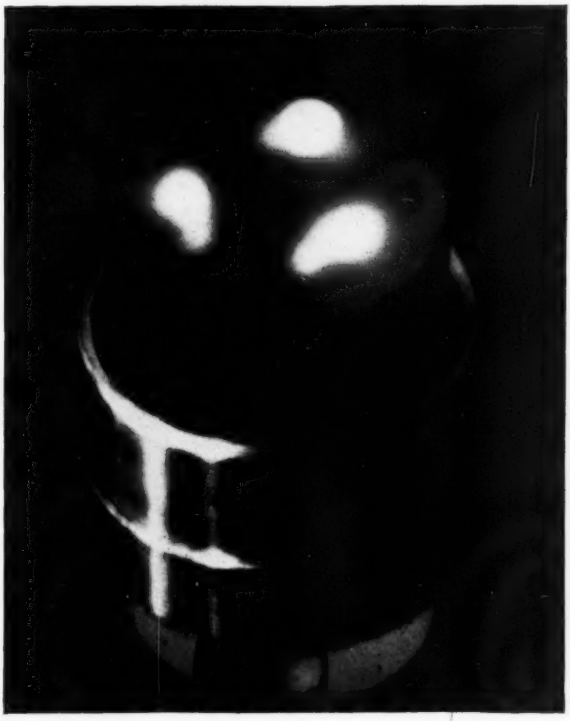


FIGURE 9.—*269 kc, mounting B, height 38.3 mm, diameter 24.715 mm*



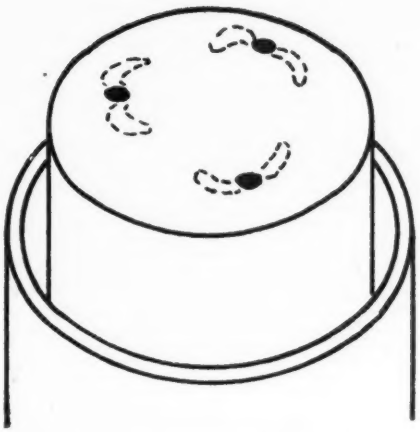


FIGURE 10.—*301 kc, mounting B, height 36.67 mm, diameter 24.715 mm*

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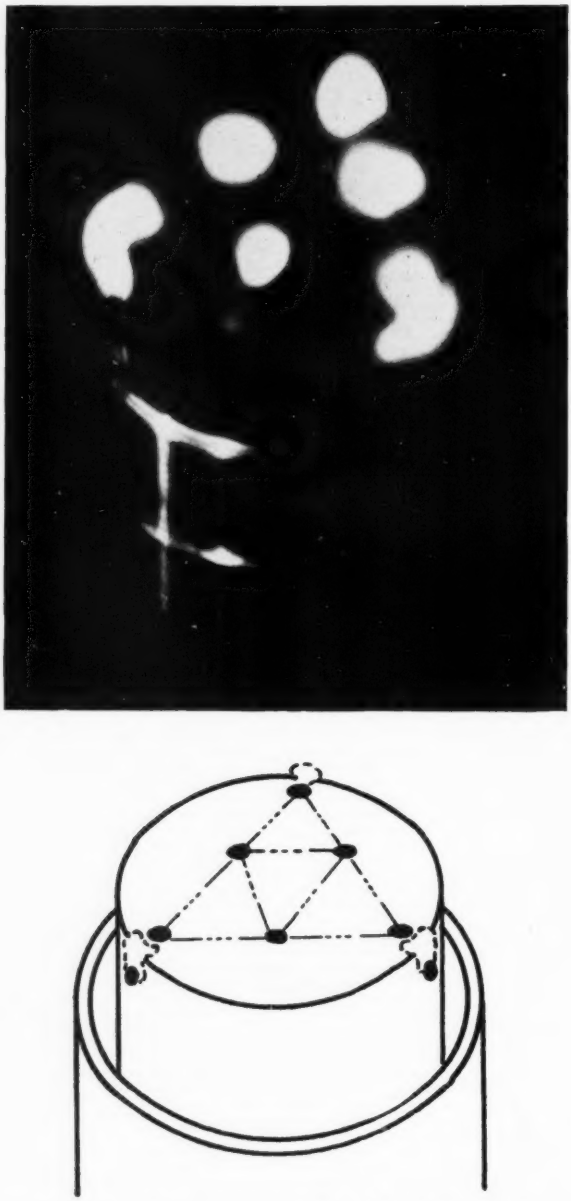
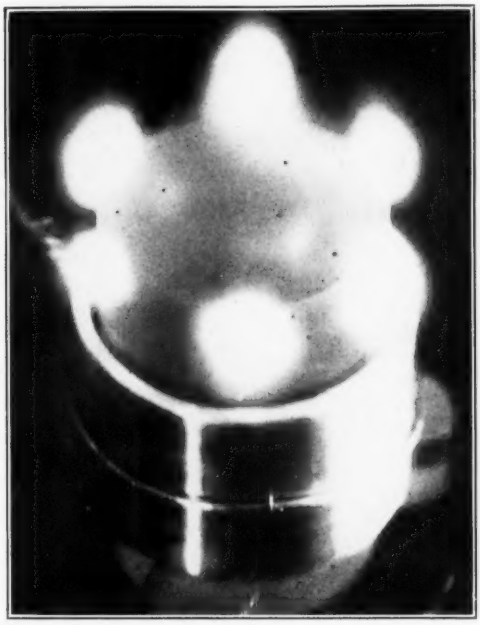


FIGURE 11.—*394 kc, mounting B, height 36.67 mm, diameter 24.715 mm*



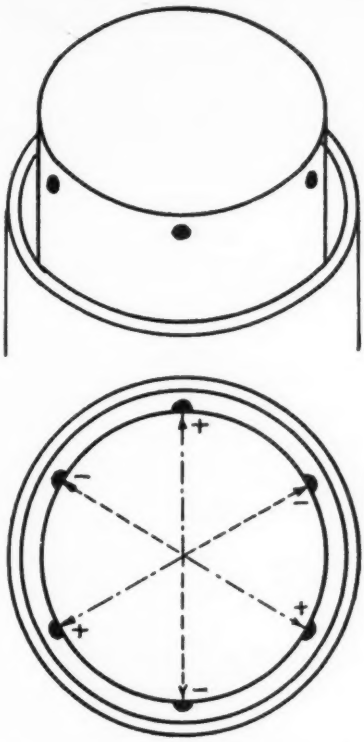


FIGURE 12.—*331 kc, mounting B, height 36.67 mm, diameter 24.715 mm*

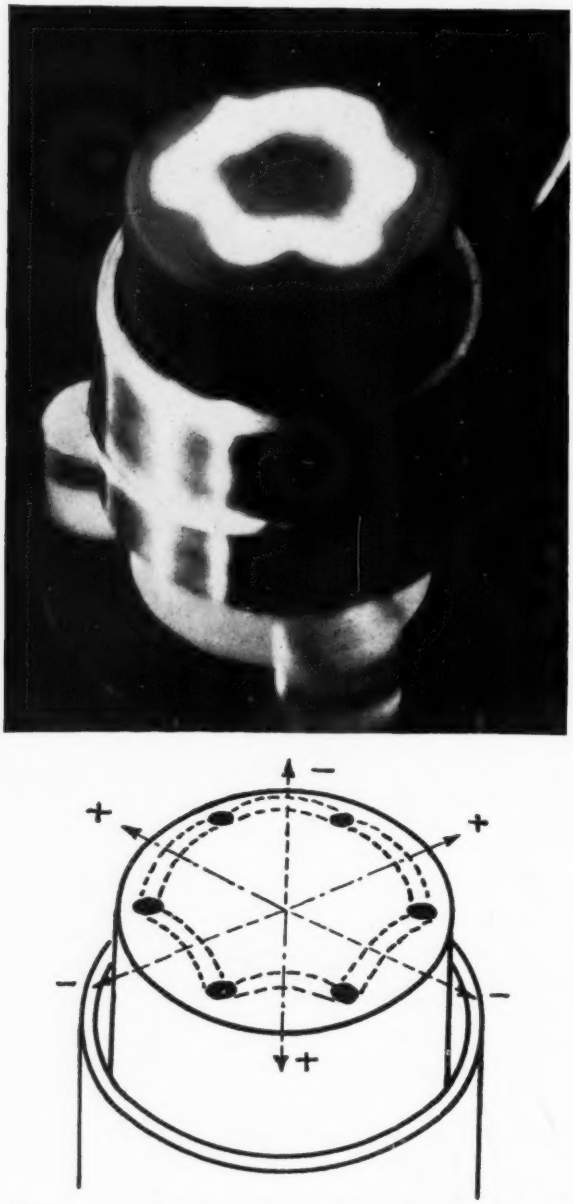


FIGURE 13.—*296 kc, mounting B, height 36.67 mm, diameter, 24.715 mm*

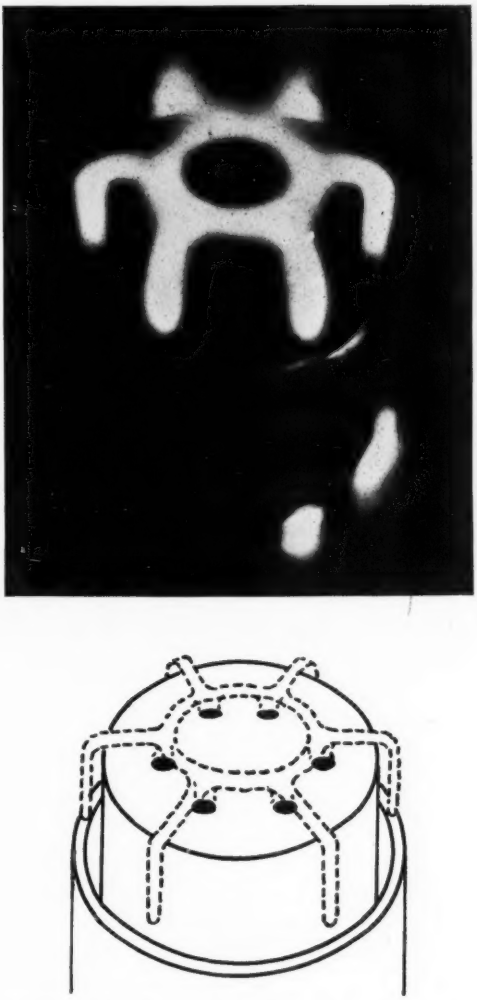


FIGURE 14.—*262 kc, mounting B, height 36.67 mm, diameter 24.715 mm*

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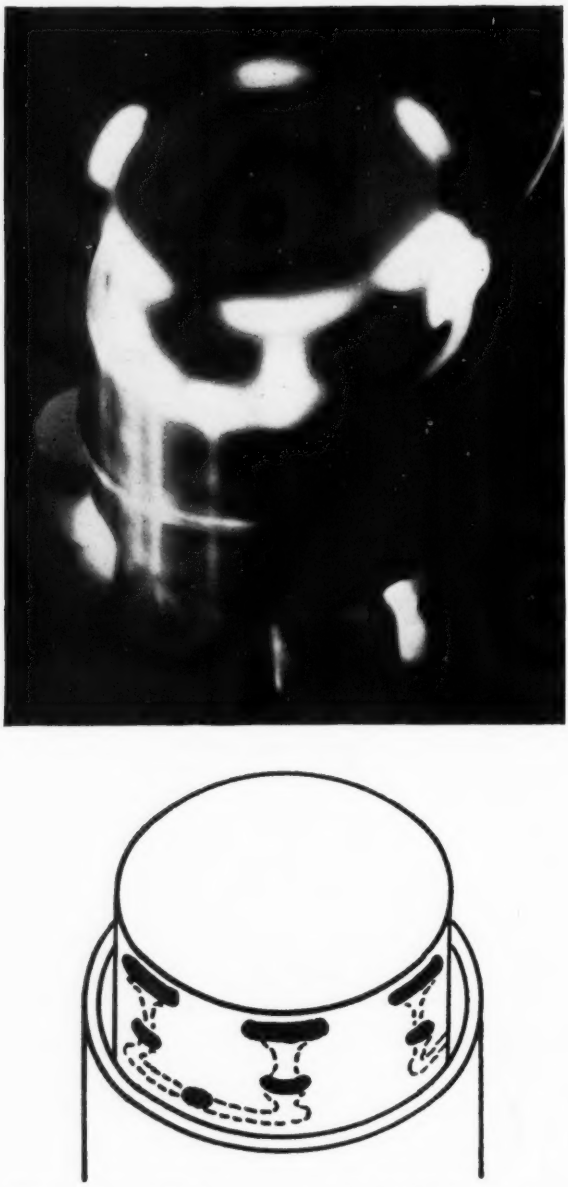

FIGURE 15.—*174 kc, mounting B, height 36.67 mm, diameter 24.715 mm*

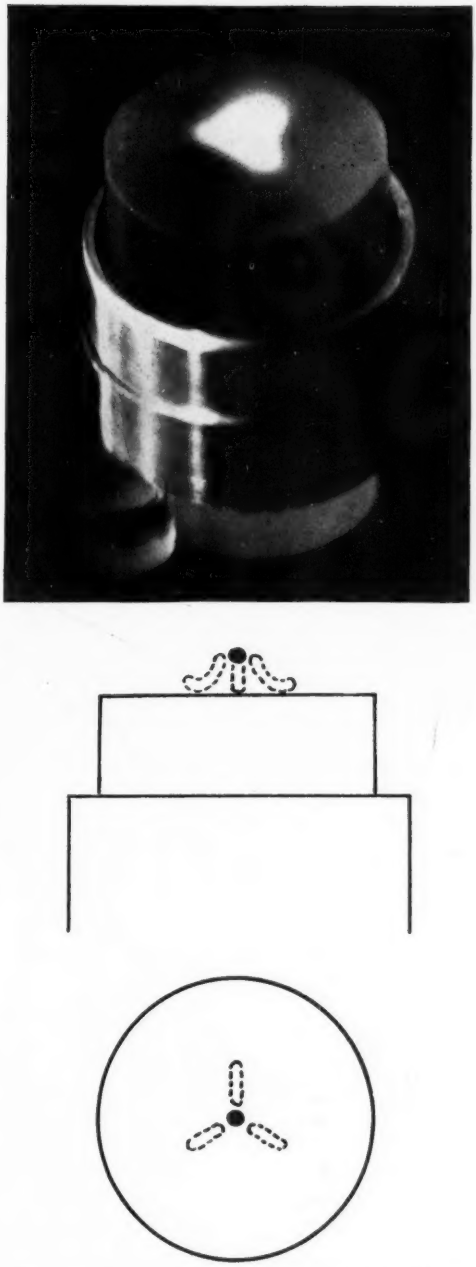

FIGURE 16.—*186 kc, mounting B, height 36.67 mm, diameter 24.715 mm*

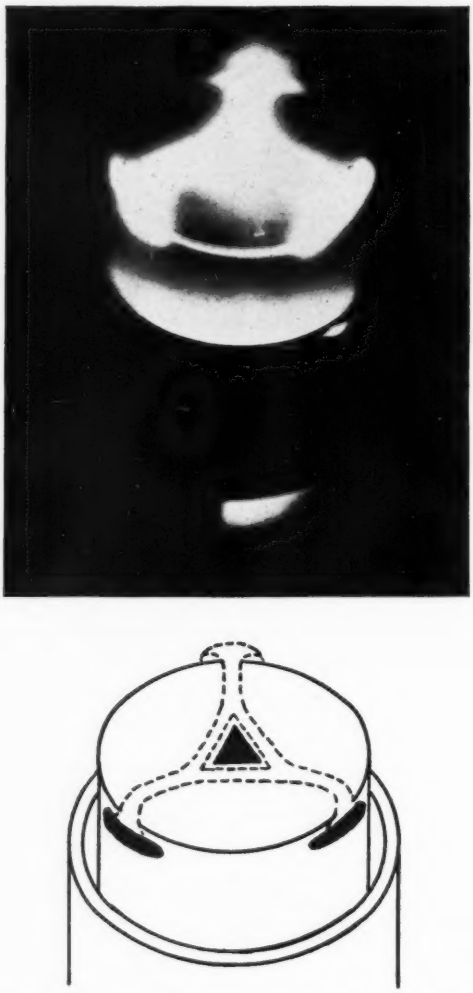

FIGURE 17.—*174–179 kc, mounting B, height 36.67 mm, diameter 24.715 mm*

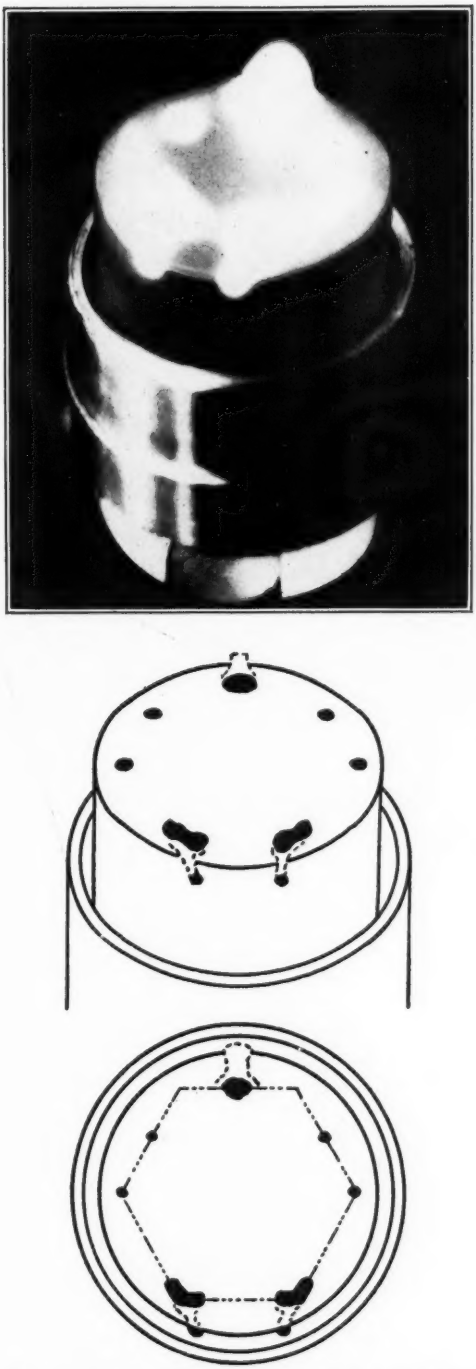

FIGURE 18.—*440 kc, mounting B, height 36.67 mm, diameter 24.715 mm*

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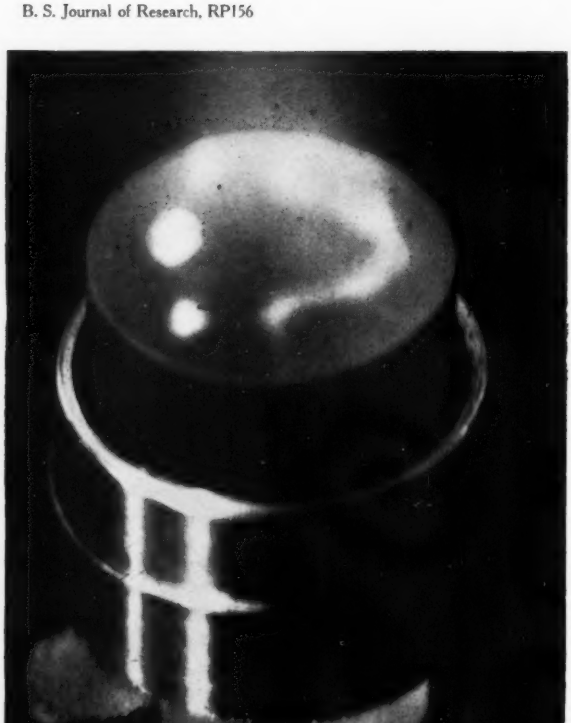

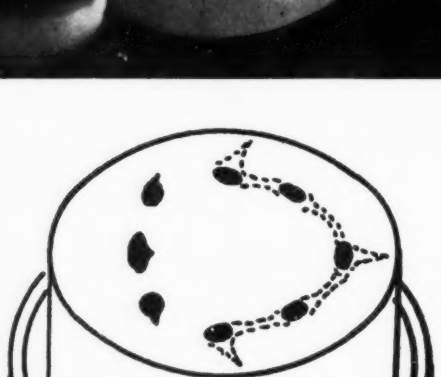

FIGURE 19.—*520 kc, mounting B, height 36.67 mm, diameter 24.715 mm*

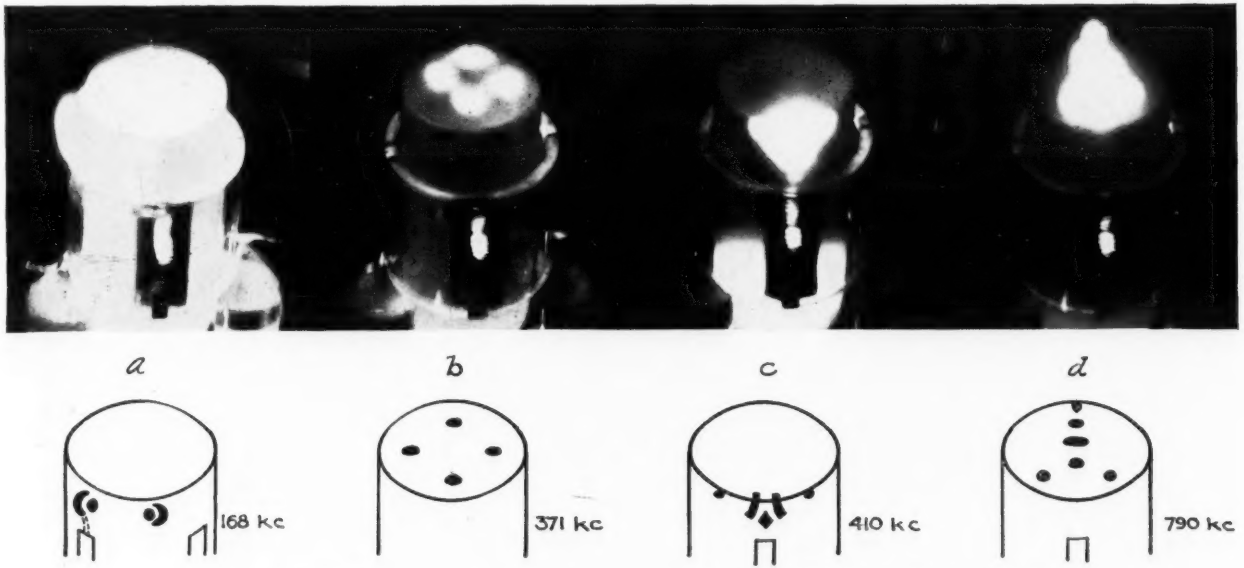

FIGURE 20.—*168, 371, 410, and 790 kc, mounting A, height 36.67 mm, diameter 17.6 mm*

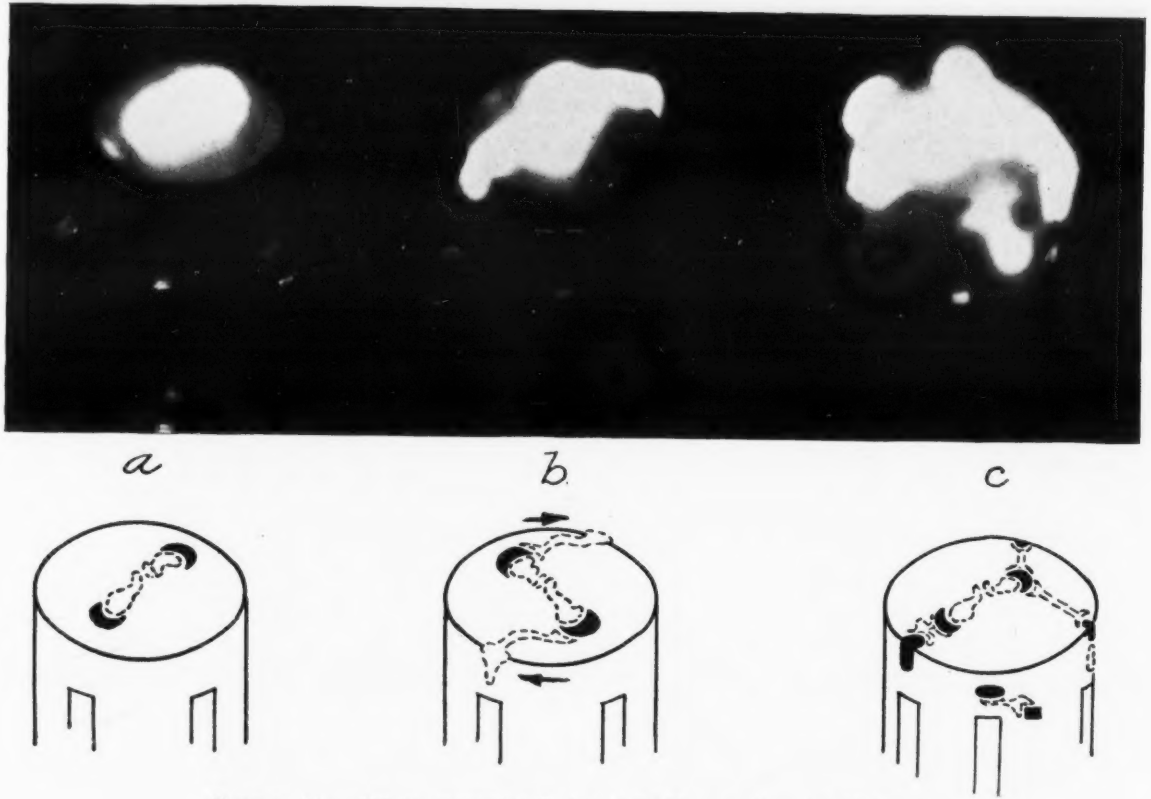

FIGURE 21.—*299 kc, mounting E, height 36.67 mm, diameter 17.6 mm*

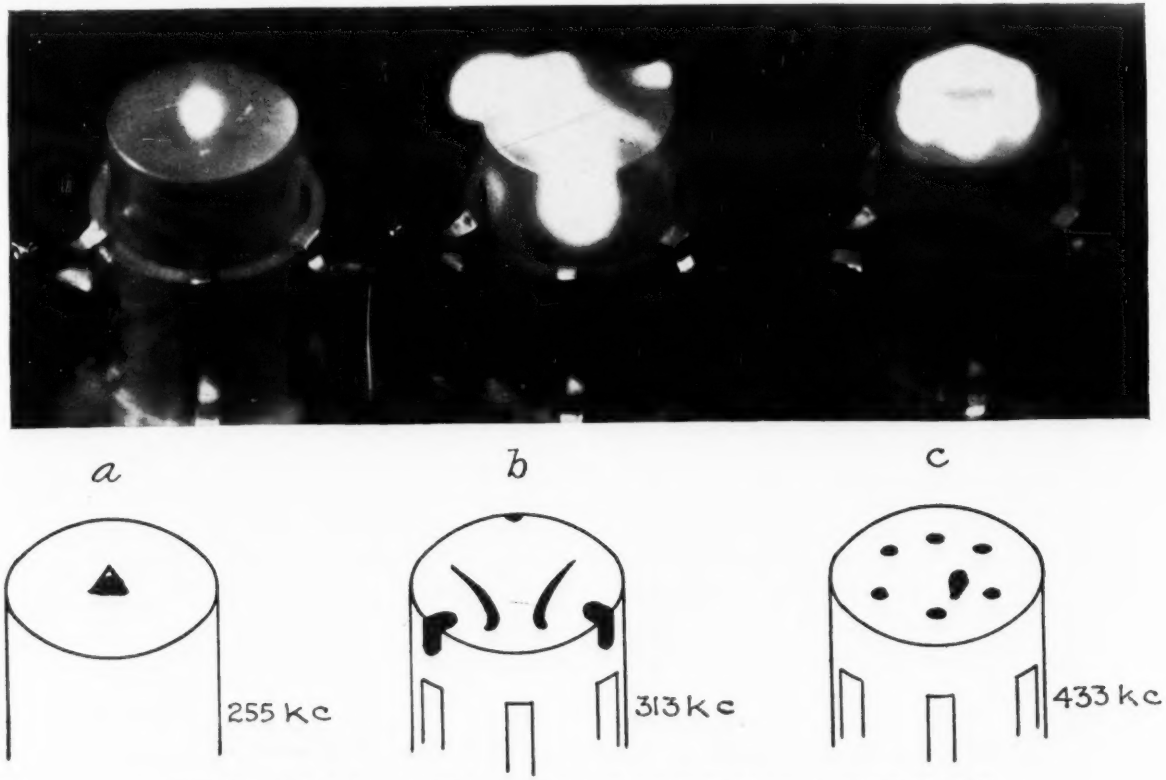

FIGURE 22.—*255, 313, and 433 kc, mounting E, height 36.67 mm, diameter 17.6 mm*

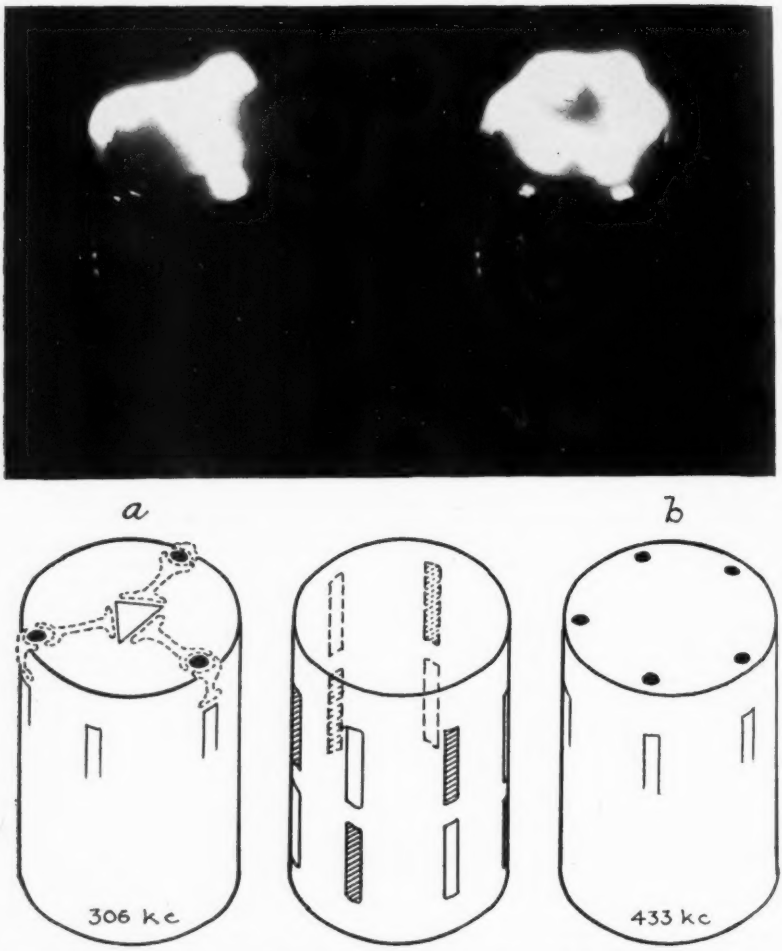

FIGURE 23.—*306 and 433 kc, mounting G height 36.67 mm, diameter 17.6 mm*

Figure 15 shows a display which accompanied the 174 kc oscillation, and Figure 16 that for the 186 kc oscillation, which latter consisted of a space charge globule elevated somewhat above the center of the top face and resting, so to speak, on its own discharge, which emanated from it in a downward direction, in the form of a tripod.

In Figure 17 is depicted a beat phenomenon between the two frequencies at which the cylinder was being simultaneously oscillated. On going up to still higher frequencies, the 440 kc oscillation shown in Figure 18 was found. It consists of large and small discharge spots. Except for the three envelope discharge points these were found to lie on the indicated hexagon. The three large discharge points did not form an equilateral triangle in this case, but this may conceivably happen for higher modes of vibration.

For the 520 kc oscillation, the pattern of Figure 19 was obtained. Here four of the seven spots appeared to lie on a parabola.

2. EXPERIMENTS WITH MOUNTINGS A, E, AND G

It seemed of particular interest to find out whether oscillations could be produced using mounting A, with its four quadrant electrodes, considering the peculiar relation of the electrode system to the three piezo-electric axes. Oscillations were nevertheless obtained, as is shown in Figure 20. The electrode system in this case consisted of thin aluminum strips pasted inside of a glass cylinder whose inside diameter exceeded the diameter of the quartz cylinder by about 2 mm.

The 168 kc oscillation, obtained with mounting A, consisted of a glow discharge in the upper left corner, coexistant with a similar one, diagonally opposite; that is, on that portion of the lower edge which can not be seen in the photograph. The diagonal effect for the 410 kc oscillation of Figure 20 (*c*), however, can be recognized at least by the general glow to be seen through the lower portion of the cylinder. The 371 kc oscillation produced four surface discharges on top of the crystal, and the 790 kc oscillation the pattern of Figure 20 (*d*).

With mounting E, which would appear to be a most natural one, embodying six electrodes placed around the cylinder, oscillations shown in Figures 21 and 22 were produced. Such a mounting may be placed in two distinctly different positions. It may be so placed that the electrodes cover either the points of maximum or the points of minimum piezo-electric polarization; that is, so placed that they fall either on or midway between the three piezo-electric axes. The former position may well be called the "Curie" or 0° mounting, and the latter the 30° mounting. Both mountings were tried, and oscillations were produced in each case. Whenever the same pattern—that is, the same oscillation—was obtained in each case, it was found that the pattern occurred at the same position on the crystal irrespective of the mounting position. Thus, in the six glow discharge pattern of the 433 kc oscillation shown in Figure 22 (*c*), the six surface discharges occurred halfway between the actual piezo-electric axes for both the 0° and 30° mounting. At this point it may be of interest to recall the pattern of Figure 13 where, also, six circular discharges were obtained on the top face, but this with the cylinder drive B. In that case the discharges were also halfway between the piezo-electric axes. Moreover, referring again to mounting E, it seems that with the 30° location of the electrodes, oscillations may be

brought in somewhat more easily, just as in ordinary piezo-electric work somewhat better response is obtained with 30° cuts than with "Curie cuts."

The 299 kc oscillation shown in Figure 21 can give patterns as indicated, depending upon gas pressure and feed back. The pattern in Figure 21 (*b*) consisted of two surface discharges interlinked by a discharge which was raised above the surface of the crystal. The position of these surface discharges, with respect to the piezo-electric axes, depends apparently upon phase relationship. When the small condenser C_1, or the regeneration control C_0, of circuit, Figure 2 (*a*), was changed by a small amount, this "doublet" turned around either by 60° or by 30°. For the former case, the "doublet" swung into the adjacent piezo-electric axis and, for the latter, into a 30° location. Since this took place without a frequency change it must have been caused by a change in phase.

The mounting G shown in Figure 23, was designed with the purpose in mind of producing torsional effects. All shaded electrodes lead to one terminal, and the remaining electrodes to the other terminal. From the discharge patterns and frequencies of oscillations obtained with this drive we must infer that the oscillations, in many cases at least, are the same as obtained with mountings B, C, D, E, and F. An interesting point about this drive is that the orders of the modes of oscillation it produces are generally found to lie in a higher range than those produced with the other mountings.

V. COMPARISON OF THE EXPERIMENTAL RESULTS

Most of the patterns shown herein, and most of those observed by the authors but not shown, strongly indicate that the vibrations of the quartz cylinder are dependent upon piezo-electricity, since the patterns indicate either directly or, at least, suggest in a partial way, the piezo-electric structure. Tawil's "strepho-electricity" must be, therefore, a case of true piezo-electricity. This dependency of vibrations upon piezo-electricity may be better understood from a study of the electric lines of force involved. Consider, for instance, mounting B, which suggested itself from Tawil's experiments. The lines of force leave the end face electrodes parallel to the optical (*Z*-axis, according to Voigt's notation) axis at first, then bend around, and finally enter the cylindrical electrode perpendicularly. Hence, there must be components along the three piezo-electric axes, which lie in the equatorial plane. These components must produce "Curie effects." In Table 1 are compiled some of the frequencies obtained either with the cylinder under a low pressure of helium gas, or in air, at atmospheric pressure. With the exception of those for mounting A, the discharge figures and the frequencies check each other more or less closely. The only frequency for mounting A which agreed with that for any of the other mountings was 433 kc. The pattern for mountings B, E, F, and G at this frequency, was that shown in Figure 22 (*c*), six surface charges located halfway between the piezo-electric axes. But the pattern found at this frequency, using mounting A, was somewhat different. It resembled a "doublet," very similar to the one shown in Figure 21 (*b*), but smaller and excentrically located, on the top face of the cylinder.

TABLE 1.—*Oscillation frequencies in kc/sec.*

Mounting A, 4 electrodes	Mounting B, cylinder mounting	Mounting E, 6 electrodes	Mounting F, 3 rings	Mounting G, 12 electrodes	Remarks
	118				With mounting F, crystal was driven in air. With all others, crystal was driven in a low pressure of helium. Height of cylinder 36.67 mm.; diameter, 17.6 mm.
125					
			150		
168				168	
			192		
203					
215					
				227	
	231				
		240			
	251		251	251	
	255	255			
257					
267			267	267	
	289	289	289	289	
		299	299		
				306	
		313			
371					
	373				
		380		380	
383					
	395	395		395	
410					
	417	417	417	417	
433	433	433		433	
	446			446	
470					
475					
	489				
		545	545		
				520	
	600			600	
790					
830				830	

With some mountings the phenomenon of recurring patterns was observed. With both mountings B and G, both the 433 and 446 kc oscillations produced the same 6-spot pattern (fig. 22 (*c*)) mentioned above. Similarly, with mounting B both the 251 and 255 kc oscillations produced the same triangular spot (shown in fig. 22 (*a*)) at the center of the top face.

VI. THEORETICAL CONSIDERATIONS

In general, there are three fundamental modes of possible natural oscillation, each of a different nature, as well as the modes of higher order for each of the three, which must be considered. Even in the relatively simple case of an isotropic substance we find that the formulas for vibrations of a body may involve three velocities of propagation, v_1, v_2, and v_3. The first two of these are due to the fact that we have a linear modulus of elasticity, E_1, and a torsional modulus, E_2, to deal with in case of longitudinal and torsional vibrations, respectively. The third velocity is due to what we may consider as a corresponding E_3 effective in the case of transverse vibrations. Thus if D denotes the density, which is 2.65 g/cc for crystal quartz:

$$\begin{aligned} v_1^2 &= E_1 D^{-1} \\ v_2^2 &= E_2 D^{-1} \\ v_3^2 &= E_3 D^{-1} \end{aligned} \qquad (1)$$

However, E_3 should not be considered as independent; a simple relation is found to exist between E_1 and E_3 such that we may con-

veniently write for the corresponding frequencies, f, of vibration in the case of a cylindrical body:

$$\text{(longitudinal)} \quad f_{long}=\frac{p}{2l}\sqrt{\frac{E_1}{D}}$$

$$\text{(torsional)} \quad f_{tors}=\frac{p}{2l}\sqrt{\frac{E_2}{D}} \tag{2}$$

$$\text{(transverse)} \quad f_{trans}=\frac{d\psi_p^2}{8\pi l^2}\sqrt{\frac{E_1}{D}}$$

where p stands for the order of the mode ($p=1$ for the fundamental) and d and l denote the diameter and height of the cylinder, respectively. The values of ψ_p for the fundamental, and some of its higher modes, are:

$$\psi_1 = 4.71$$
$$\psi_2 = 7.85$$
$$\psi_3 = 11.0$$
$$\psi_4 = 14.1$$
$$\psi_5 = 17.3$$

From this it can be seen that for a cylinder, only the transverse modes of oscillation are affected by the size of its cross section, that is, by its diameter. This is true, however, only when the cylinder height is large compared with the diameter.

The above formulas are all well known. Moreover, it is evident that those for torsional and transverse vibrations may be rather conveniently expressed in terms of that for longitudinal vibrations. Thus we may write:

$$f_{tors}=\frac{f_{long}}{\sqrt{2\ (1+\mu)}} \tag{3}$$

Where μ may have values between 0.2 and 0.5 depending upon the values of E_1 and E_2. And for the transverse frequency we obtain:

$$f_{trans}=\frac{\pi\ (2p+1)^2}{16\ p}\cdot\ \frac{d}{l}f_{long} \tag{4}$$

from which, for the fundamental mode:

$$f_{trans}\Big|_{p=1} = 1.767\ \frac{d}{l}f_{long} \tag{5}$$

These formulas will give, of course, no very reliable values for crystalline quartz since the modulus of elasticity, although constant in the equatorial plane (perpendicular to the optical axis), is different for all other directions. Fortunately, however, earlier experimenters in the field[8] have determined the longitudinal modulus E_1, as well as the torsional modulus E_2, along the optical axis. They are:

$$E_1 = 10.304\times 10^{11}$$
$$E_2 = 5.085\times 10^{11}$$

[8] Voigt, Riecke, Pockels, and others.

The values under the radicals in (2) represent velocities, as may be seen by referring to (1), and become, with the above values of elasticity, and the density given previously:

$$v_1 = 6.24 \times 10^5 \text{ cm/sec.}$$

$$v_2 = 4.38 \times 10^5 \text{ cm/sec.}$$

For the longitudinal and torsional modes of oscillation of a cylinder of crystalline quartz cut along the optical axis, therefore, we have:

$$\left.\begin{aligned} f_{long} &= \frac{312\ p}{l} \\ f_{tors} &= \frac{219\ p}{l} \end{aligned}\right\} \text{kilocycles/sec.} \qquad (6)$$

where the length, l, of the cylinder is expressed in centimeters and p stands for 1, 2, 3, 4, etc., according to the order of the mode.

For the transverse modes the expression in (2), together with the above value of v_1, gives:

$$f_{trans} = 24.8\ \frac{d\ \psi_p^{\,2}}{l^2} \text{ kilocycles/sec.} \qquad (7)$$

where both the length, l, and the diameter, d, of the cylinder are expressed in centimeters. As far as the fundamental of this transverse mode is concerned (5) and (6) check (7) for the value of $\psi_p = 4.71$, and lead to:

$$f_{trans}\Big|_{p=1} = 550 \times \frac{d}{l^2} \qquad (8)$$

Of course, formula (7) must be considered as an approximation because of the lateral effect. But it should give values sufficiently close to warrant the speculation undertaken in Table 2. In this table are compiled for comparison calculated and experimental values of frequency (for the larger diameter crystal, $d = 2.4715$ cm). It appears that most of the torsional oscillations were obtained, including the fundamental, which has hitherto not been mentioned. No description of the pattern for this fundamental mode is given because the oscillation could be produced only in air, at atmospheric pressure, the reason for which would no doubt be found in a study of the characteristics of the particular drive used.

TABLE 2.—*Theoretical and experimental frequencies for cylinder, in kc/sec.*

	Order of mode	$p=1$	$p=2$	$p=3$	$p=4$	$p=5$	$p=6$
$f_{longitudinal}$	Calculated (equation 6)	85.2	170.4	255.6	340.8	426.0	511.2
	Measured		174	257			520
$f_{torsional}$	Calculated (equation 6)	59.8	119.6	179.4	239.2	299.0	358.8
	Measured	63	118	179		296	331
$f_{transverse}$	Calculated (equation 7)	101	281	552	906		
	Measured		288				

Length, $l = 3.667$ cm; diameter, $d = 2.4715$ cm; $d/l^2 = 0.184$.

It is interesting to note that for the cylinder of smaller diameter ($d=1.76$ cm), but of the same length there was found a frequency corresponding exactly to one appearing in Table 2, namely, 118 kc. This indicates that for this particular mode and order at least the frequency is independent of cross section.

VII. CONCLUSION

Although there are reasons why the comparison in Table 2 is of a speculative nature, nevertheless, after examining it, it is very difficult to believe that all the oscillations are of the same mode even if they were all obtained using the same mounting B and drive *a*. The table seems to indicate, however, that torsional oscillations predominate with this combination of mounting and drive.

As was pointed out in the description of the patterns shown, in most cases the hexagonal formation was indicated, and in many cases the actual piezo-electric axes were either marked out by discharge points or indicated by points midway between. A pertinent point in this respect, and also in its relation to Tawil's work, is that the frequencies of two of the most striking examples of this indication of piezo-electric axes appear to correspond, as shown in Table 2, with torsional vibrations. In Table 1 is to be found a second interesting fact in this respect. It is that most of the frequencies produced using the ring mounting (mounting B) can also be produced using the 6 and 12 electrode drives (mountings E and G, respectively).

In general, the observed facts of these oscillations seem to be in perfect harmony with the previously known phenomena of piezo-electricity; no need for other explanations appears.

WASHINGTON, September 3, 1929.

TRANSVERSE TESTS OF H-SECTION COLUMN SPLICES

By James H. Edwards, H. L. Whittemore, and A. H. Stang

ABSTRACT

Plates were welded to the outer edge of the inside faces of the flanges of 3-foot lengths of 10, 12, and 14 inch H sections. The H sections were joined in pairs by splice plates bolted to these welded plates to represent a spliced section of column for use in a steel-frame building. The specimens so formed were tested as beams on a 66-inch span with loads at the quarter points. Four specimens were tested with the splice plates and H section webs parallel to the applied loads which were in a vertical plane; three specimens were tested with the splice plates and H section webs perpendicular to the applied loads.

The behavior of the specimens is described and a method of stress analysis suitable for use in designing similar splices is developed.

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I. INTRODUCTION

Steel structures are composed of large members, such as columns and floor beams, joined or fastened together with small plates, angles, or other shapes which are commonly referred to as structural details. The complex distribution of stress in the details requires that tests be made to show whether the methods used in determining the size of the details result in safe and economical structures. If for some reason a detail is changed, further tests should be made to determine the effect of the change.

The adoption of welding in the fabrication and erection of structural steel has brought about the modification of many structural details. The present investigation was undertaken to determine the effect of substituting welding for riveting in the fabrication of details used in splicing columns of steel-frame buildings and of changing the location of the splice plates from a position parallel to the flanges of the columns to one parallel to the webs of the columns.

The columns of steel-frame buildings are commonly made in 2-story lengths and are connected at alternate floors by splices. The weight of the structure and its contents and the wind pressure against the

structure produce compressive, bending, and shearing stresses in the columns and splices. At the column connections or joints, the splice plates joining the ends of the columns resist the bending and shearing stresses. The compressive stress at the joints is commonly assumed to be carried by the columns only. The stress is transferred from the upper to the lower column by bearing.

The tests reported in this paper were made to investigate the strength and other properties of welded splice connections of H sections subjected to bending. No tests were made to determine the resistance of this type of connection to shearing stresses.

Columns in steel-frame buildings are commonly 10, 12, or 14 inches wide. Data on the strength of splices of these sizes of columns were desired, using as few specimens as possible. As wind pressure on a building may produce loads on the columns in the direction of either of the transverse axes, it was necessary to test some specimens under loads parallel to one axis and other specimens under loads parallel to the other axis.

Because the specimens were loaded as simple beams, they will be called "beams" in this report. It should be remembered, however, that they represent spliced column sections under the action of bending stresses.

The American Bridge Co. furnished the specimens which were designed by James H. Edwards, chief engineer. O. E. Hovey, assistant chief engineer, and other members of the company's engineering staff assisted in making the tests. Prof. Elmer O. Bergman, research associate, contributed considerably to the analysis of the test data and edited the manuscript.

TABLE OF SYMBOLS

B_U = Force exerted by upper bolts on plate.
B_L = Force exerted by lower bolts on plate.
C = Resultant compressive force.
T = Resultant tensile force.
$N.\ A.$ = Neutral axis.
C_1 = Compressive force on upper flange of H beam at spliced section.
C_2 = Resultant of B_U and C_1.
C_3 = Resultant of W_U and C_1.
W_U = Force exerted through upper weld on H beam.
W_L = Force exerted through lower weld on H beam.
S_t = Tensile stress.
S_c = Compressive stress.
S_s = Shear stress in bolts.
S_{sw} = Shear force per unit length in weld.

II. SPECIMENS

Plates were placed parallel to the webs of the H sections and welded to the inside faces of the flanges as shown at A in Figure 1. The welds for the 10 and 14 inch H sections with the exception of column C14–B3B2W, which had fillet welds, were single-bevel butt welds as shown in Figures 2 and 3. The welds for the 12-inch H sections were $\frac{5}{16}$-inch fillet welds as shown in Figures 4 and 5. The distance from the ends of the plates to the ends of the H sections was one-half inch. The angles welded to the H section at B in Figure 1 were

FIGURE 1.—H *section showing plate welded to inside faces of flanges at A*

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used in an investigation of the strength of welded shelf angles which will be reported in a later paper.

The H sections were 3 feet long and 10, 12, or 14 inches wide. They were fastened together in pairs with either two or four splice plates bolted to the plates which had been welded to the H sections.

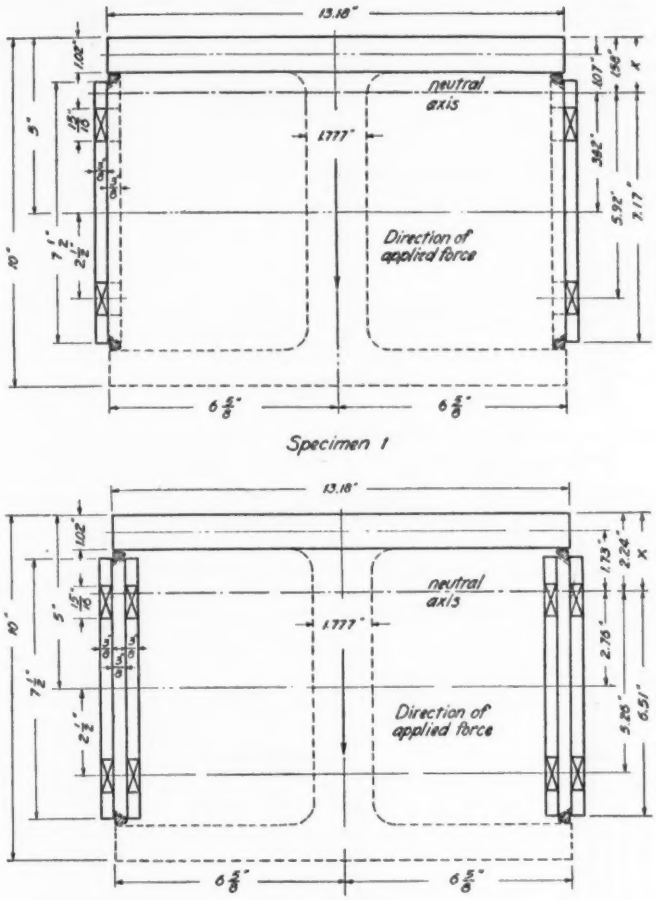
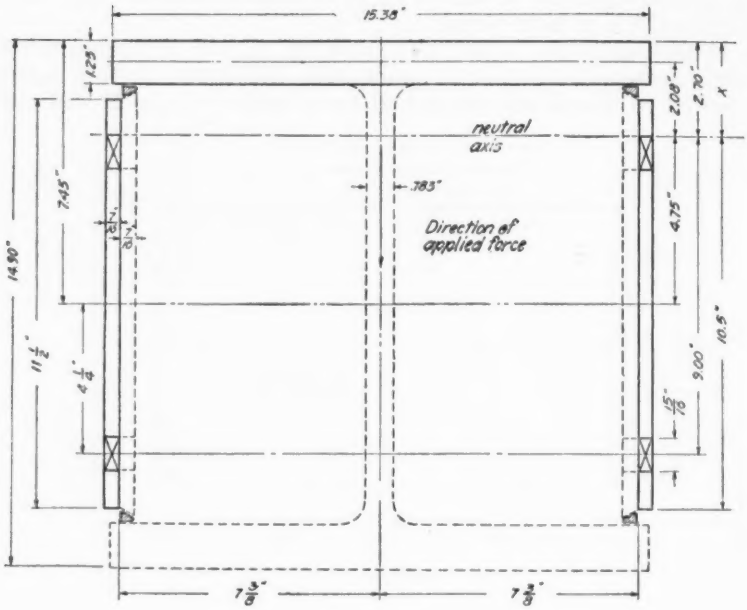


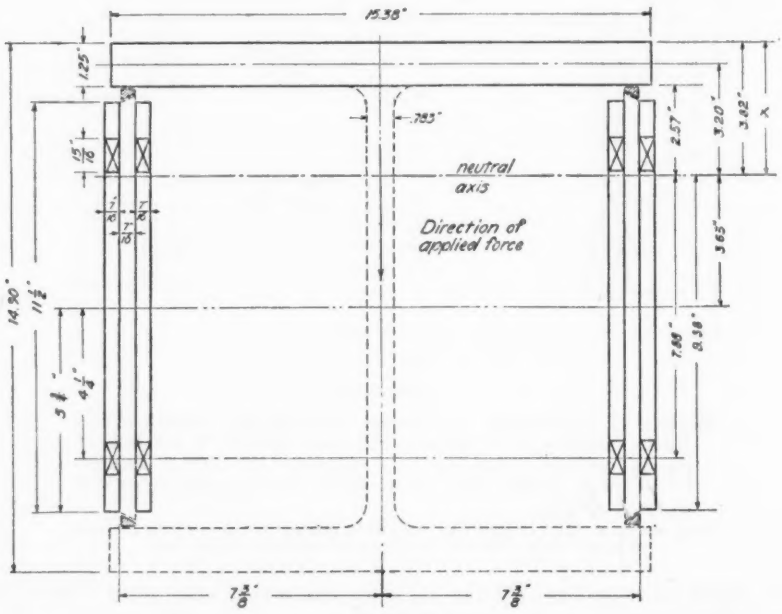
FIGURE 2.—*Specimen 1; column C10–B1B4; column C10–B2B4; single splice plates, SP1, load parallel to the web of the* H *sections. Specimen 2, column C10–B1B4, column C10–B2B4, double splice plates SP1, load parallel to the web of the* H *sections*

Cross section at splice of specimens with loads parallel to web, showing position of neutral axis. Portions carrying stress indicated by full lines.

The bolts were seven-eighths inch in diameter and were placed in two rows parallel to the longitudinal axes of the H sections. The plates had $^{15}/_{16}$-inch punched holes. One splice plate was placed outside the welded plates on each side of the specimens that had single splice plates. (Figs. 2 to 6.) Two splice plates, one inside and one outside the welded plates, were used on each side of the specimens that had double splice plates. (Fig. 7.)



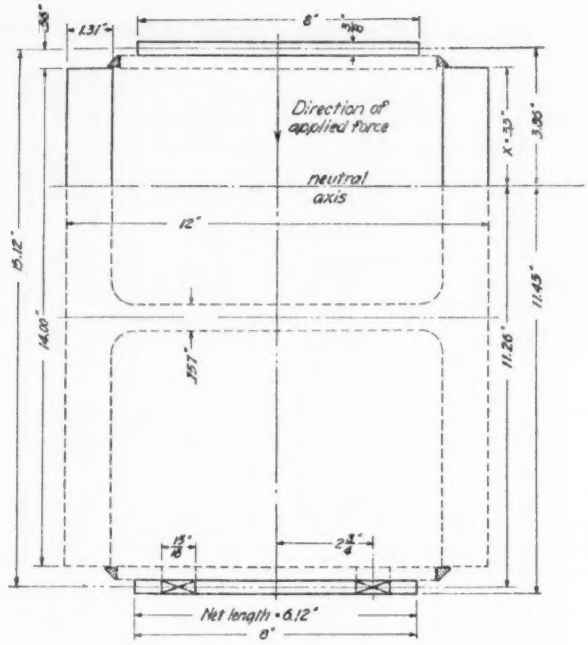
Specimen 3



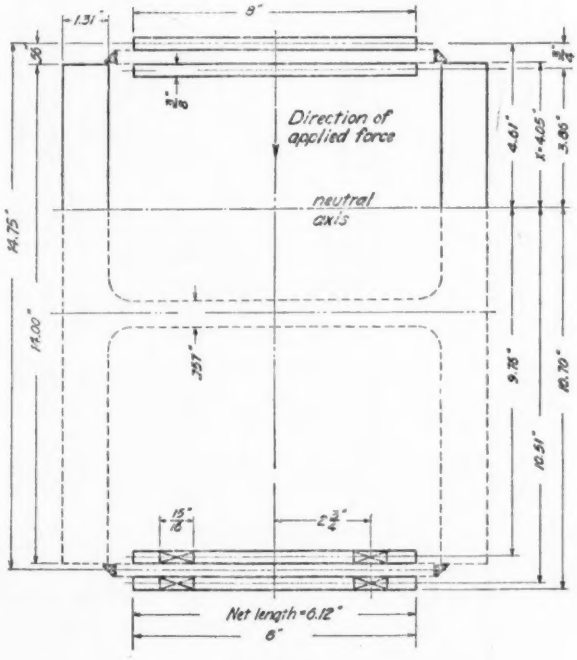
Specimen 4

FIGURE 3.—*Specimen 3, column C14–B1B4, column C14–B2B4, single splice plates, SP3, load parallel to the web of the* H *sections. Specimen 4, column C14–B1B4, column C14–B2B4, double splice plates, SP3, load parallel to the web of the* H *sections*

Cross section at splice of specimens with loads parallel to web, showing position of neutral axis. Portions carrying stress indicated by full lines.



Specimen 5



Specimen 6

FIGURE 4.—*Specimen 5, column C12–B3B4; single splice plates, SP2; load perpendicular to web of the* H *sections. Specimen 6; column C12–B1B2W; column C12–B3B4, double splice plates, SP2; load perpendicular to the web of the* H *sections*

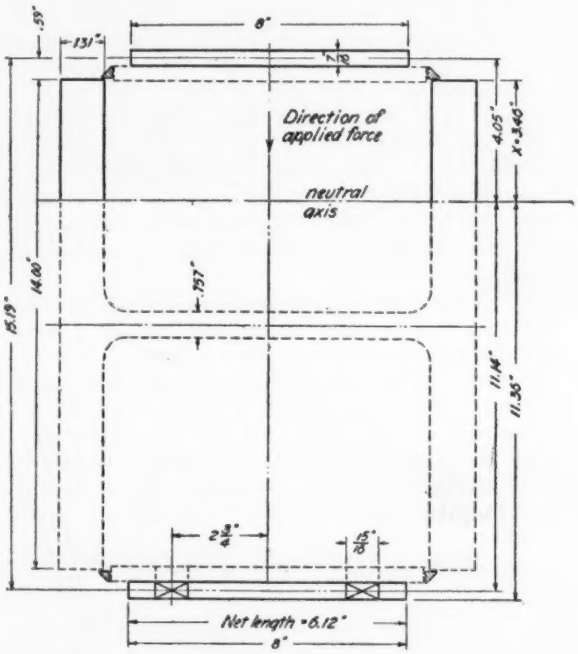
Cross section at splice of specimens with loads perpendicular to web, showing position of neutral axis. Portions carrying stress indicated by full lines.

TABLE 1.—*Dimensions of specimens and results of tests*

	Specimen number													
	1		2		3		4		5		6		7	
H section	10 inches, 140 lbs./ft.		10 inches, 140 lbs./ft.		14 inches, 165 lbs./ft.		14 inches, 165 lbs./ft.		12 inches, 150 lbs./ft.		12 inches, 150 lbs./ft.		{12 inches, 150 lbs./ft. {14 inches, 165 lbs./ft.	
Welded plates, size.....inches	7¾ by ⅜ by 9		7¾ by ⅜ by 9		12 by 7/16 by 12¼		12 by 7/16 by 12¼		9 by ⅜ by 9¼		{9 by ⅜ by 9¼ {12 by 7/16 by 9¼		12 by 7/16 by 9¼. 12 by 7/16 by 12¼.	
Splice plates, size.....do	7½ by ⅜ by 19		7½ by ⅜ by 19		11½ by 7/16 by 25		11½ by 7/16 by 25		8 by ⅜ by 19		8 by ⅜ by 19		8 by 7/16 by 27.	
Splice plates.....number	2 (single)		4 (double)		2 (single)		4 (double)		2 (single)		4 (double)		2 (single).	
Splice plates.....position	Vertical		Vertical		Vertical		Vertical		Horizontal		Horizontal		Horizontal.	
Bolts.....total number	24		24		32		32		24		24		32.	
Bearing plate, size.....inches													14½ by 2 by 15½.	
Moment of inertia.....in.⁴	84		141		357		583		367		617		427.	
Failure	Splice plates failed in tension.		Splice plates failed in tension, welded plates showed signs of bearing failure.		Bottom rows of bolts sheared, in one H section.		Welded plates failed along lower line of bolts, welds sheared, bolts started to shear.		Plates bowed up, 4 inner bolts sheared, and welds failed at inner end on one H section.		Failed in bearing, welded plate sheared lengthwise, welds opened up near ends.		Lower splice plate failed in tension.	
	Load at—		Load at—		Load at—		Load at—		Load at—		Load at—		Load at—	
	Yield point	Maximum	Yield point	Maximum	Yield point	Maximum	Yield point	Maximum	Yield point	Maximum	Yield point	Maximum	Yield point	Maximum
Load.....pounds	30,000	102,450	60,000	218,000	70,000	279,950	220,000	547,500	55,000	216,670	130,000	340,000	60,000	312,000
Bending moment.....lbs.-in.	247,500	845,200	495,000	1,798,500	577,500	2,309,600	1,815,000	4,516,900	453,800	1,787,500	1,072,500	2,805,000	495,000	2,574,000
Maximum tensile stress in splice plates.....lbs.-in.²	21,200	72,500	22,900	83,200	17,000	68,000	29,200	72,700	14,200	55,750	18,600	48,600	13,200	68,600
Maximum compressive stress in H section.....lbs.-in.²	4,700	16,000	7,900	28,600	4,400	17,500	11,900	29,550	4,100	16,100	7,000	18,400	4,000	20,900
Shearing stress in lower bolts.....lbs.-in.²	8,900	30,400	9,100	33,000	10,000	39,800	16,100	40,100	8,900	35,000	11,700	30,600	7,200	37,500
Bearing stress on lower bolts and plates.....lbs.-in.²	16,300	55,500	33,200	120,500	15,600	62,300	50,600	125,800	16,200	64,000	41,700	109,000	11,300	59,000
Shearing stress in lower welds.....pounds per linear inch	1,590	5,420	3,200	11,500	1,790	7,170	5,700	14,100	1,800	7,000	4,500	11,800	1,400	7,500

The properties and dimensions of the specimens are given in Table 1. Figure 7 shows a specimen in the machine before testing. The cross sections of the specimens are given in Figures 2 to 5. The dimensions of the H sections are the nominal dimensions given in Carnegie Beam Sections (1st ed., 1927).

Four specimens were tested with the loads parallel to the splice plates and to the webs of the H sections as shown in Figure 7. Two of these were composed of 10-inch H sections (fig. 2), the other two were of 14-inch H sections (fig. 3). One specimen of each size had single, the other had double splice plates. The same H sections were



Specimen 7

FIGURE 5.—*Specimen 7, column C14–B3B2W, column C12–B1B2W, bearing plate, C12F, between columns, single splice plates, SP4, load perpendicular to the web of the* H *sections*

Cross section at splice of specimens with loads perpendicular to web, showing position of neutral axis. Portions carrying stress indicated by full lines.

used for the specimens with single and with double splice plates, the specimens with single plates being tested first. It was believed that the behavior of 12-inch specimens could be predicted with sufficient accuracy for design purposes from the data on the 10 and 14 inch specimens.

Three specimens were tested with loads perpendicular to the splice plates and webs as shown in Figure 6. One specimen consisted of 12-inch H sections and single splice plates and one of 12-inch H sections and double splice plates. (Fig. 4.) Used in conjunction with the data from specimens with loads parallel to the splice plates, the

results from these two specimens should give a good indication of the behavior of the 10 and 14 inch specimens under loads perpendicular to the splice plates. The third specimen in this group consisted of one 12-inch and one 14-inch H section with a bearing plate between and with single splice plates. (Fig. 5.) It was included to show the effect of a difference in width of the H sections.

III. TEST PROCEDURE

1. LOADING OF SPECIMENS

Specimens 1, 3, and 5 were tested in the bureau's 600,000-pound capacity testing machine. Because of the larger loads required to produce failure, the other specimens were tested in the 10,000,000-pound capacity machine. The specimens were tested as simple beams on a 66-inch span with loads applied at the quarter points.

In the 600,000-pound machine the specimen was placed on 2½-inch rollers which were free to roll so as to avoid axial constraint in the specimen. A loading beam rested on 2-inch rollers placed on the specimen at the quarter points. The spherical bearing block of the testing machine was applied to a 2-inch roller placed at the midspan of the loading beam.

The method of loading specimens in the 10,000,000-pound machine is shown in Figure 7. The pins in the end supports were 2½ inches in diameter and the rollers at the quarter points of the specimen were 2 inches in diameter. The lower platen of the testing machine has a spherical bearing which was adjusted at the beginning of a test to produce equal bearing on the rollers on the top of the specimen. No provision was made to eliminate axial constraint in these specimens. It was decided that the expense of providing the required number of rollers to permit longitudinal movement was not justified.

2. MEASUREMENT OF DEFLECTION

Wires were stretched on each side of the specimens between points directly over the supports as shown in Figure 7. The deflections of the specimens were obtained by observing the positions of the wires in a mirror having a scale attached. The scale was graduated in tenths of an inch and the deflection was read by estimation to the nearest hundredth of an inch. Readings were taken at 5,000-pound increments of load for specimens 1 and 5, and at 10,000-pound increments for the others.

IV. TEST RESULTS

The load-deflection curves for the specimens are shown in Figure 8. Figure 9 gives the curve for specimen 4 plotted to a scale which allows the deflection at higher loads to be shown. The cross lines on the curves of Figures 8 and 9 are placed at the loads for which the deflection ceased to be proportional to the loads, and these values are listed in Table 1 as "yield point" loads. The maximum load for each specimen is also given in Table 1. The meaning of the dash lines in Figures 8 and 9 will be explained later.

A detailed account of the behavior of the specimens follows.

Specimen 1.—Ten-inch H sections, single splice plates, loads parallel to web. The splice plates failed in tension across the net section

FIGURE 6.—*Specimen 7 after transverse test; 12-inch and 14-inch* H *section with bearing plate, loads perpendicular to web*

Lower splice plate failed in tension.

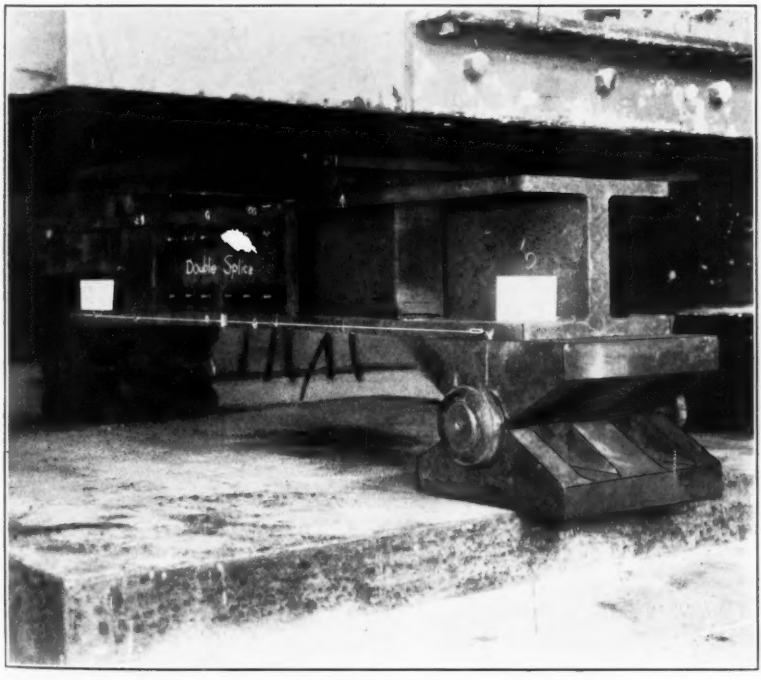


FIGURE 7.—*Specimen 2 before the transverse test; two 10-inch* H *sections; loads parallel to web*

Splice plates failed in tension; welded plates showed signs of bearing failure.

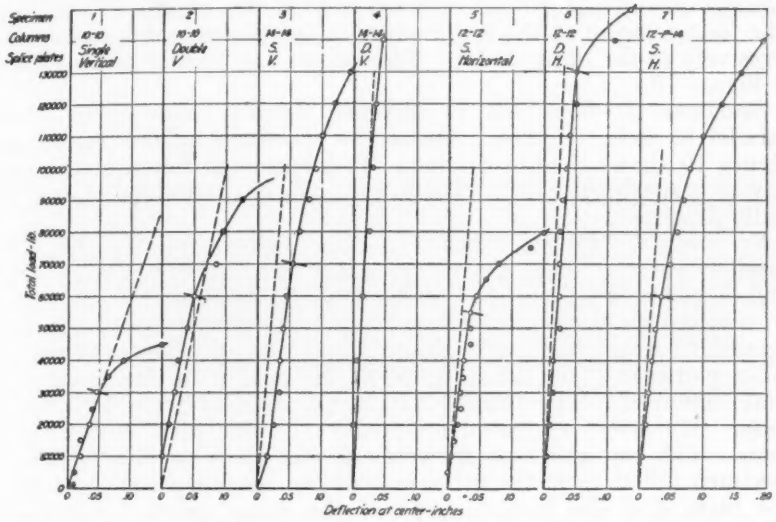


FIGURE 8.—*Load-deflection curves for spliced* H *sections, specimens 1–7.*

Full lines indicate measured deflection. Dash lines are deflection of a beam with similar loading having a constant moment of inertia equal to that computed for the weakest section of the test beam.

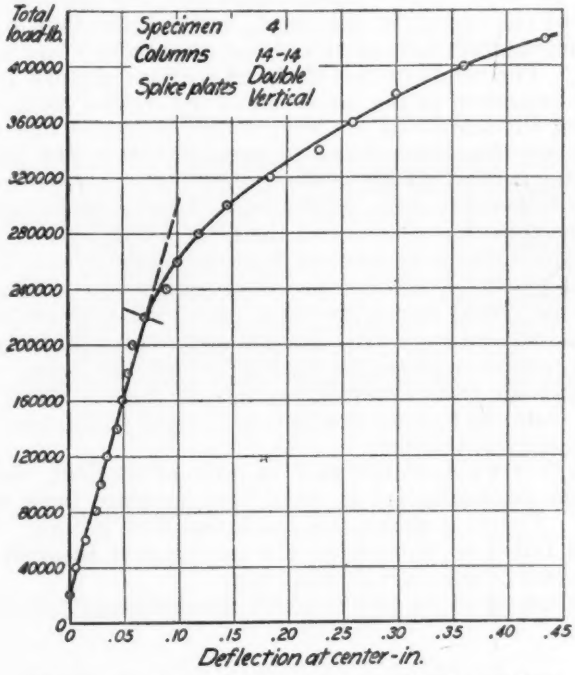


FIGURE 9.—*Load-deflection curve for spliced* H *sections, specimen 4, showing deflection at higher loads*

through one of the groups of holes nearest the middle of the plate. The failure began at the lower edges of the plates and extended progressively to the upper holes. The failure was similar to that shown in Figure 10.

Specimen 2.—Ten-inch H sections, double splice plates, loads parallel to web. Figure 7 shows the specimen before testing, and Figure 10 shows it after testing. This specimen failed in the same way that specimen 1 did. The lower holes in the welded plates were badly deformed.

Specimen 3.—Fourteen-inch H sections, single splice plates, loads parallel to web. The splice plates scaled at a load of 218,000 pounds. The eight lower bolts in one of the H sections sheared.

Specimen 4.—Fourteen-inch H sections, double splice plates, loads parallel to web. Figure 11 shows the specimen after test with the splice plates in place, and Figure 12 shows it with one outer splice plate removed. The welded plates failed in bearing against the bolts. The holes elongated noticeably and one plate split between holes. The top and bottom welds of one plate on one side of the specimen failed. On the other side of the specimen the top weld of one plate and the bottom weld of the other failed. These weld failures occurred after the maximum load on the specimen had been reached. The lower rows of bolts started to shear. The webs of the H sections over the supports scaled, and the H sections were permanently bent and distorted.

Specimen 5.—Twelve-inch H sections, single splice plates, loads perpendicular to web. The welded plates and the splice plate on the lower side of the specimen deformed, as the deflection increased, so that the longitudinal axis of the plates approached the webs of the H sections. The welds in one of the H sections sheared for a length of 3 inches beginning at the inner end of the welded plate. The four bolts nearest the middle of the joint in this H section sheared.

Specimen 6.—Twelve-inch H sections, double splice plates, loads perpendicular to web. Figure 13 shows the specimen after test with the bottom splice plate removed. Only one H section from specimen 5 could be used in this specimen as the lower welded plate of the other sheared. The 12-inch H section from specimen 7 was substituted. The welded plates on this section were longer and thicker and had two additional holes. Since the splice plates were symmetrical, these two extra holes were not used. The thinner welded plate on the lower side of the specimen failed in bearing against the bolts. The holes elongated and the plate sheared between the holes. The welds failed for a short distance beginning at the outer end of the plate. All the lower bolts started to shear.

Specimen 7.—Twelve-inch and 14-inch H sections, single splice plates, loads perpendicular to web, bearing plate between ends of H sections. Figure 6 shows the specimen after failure. The lower splice plate failed in tension on the net section through the holes nearest the end of the 14-inch H section.

A brief summary of the way in which the specimens failed is given in Table 1.

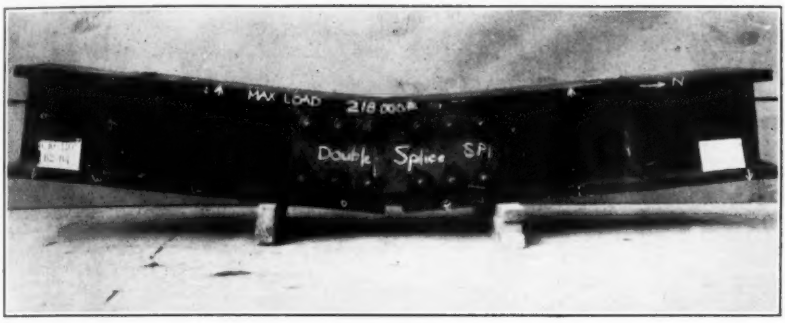


FIGURE 10.—*Specimen 2 after transverse test; 10-inch* H *sections; double splice plates; loads parallel to web of* H *section*

Splice plates failed in tension. Specimen 1 failed in a similar way.

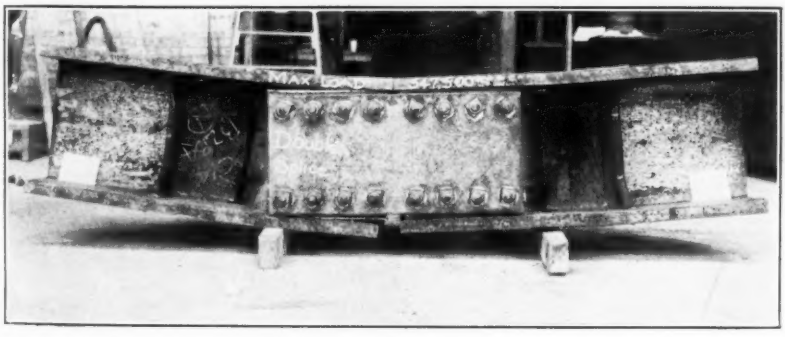


FIGURE 11.—*Specimen 4 after transverse test; 14-inch* H *sections; double splice plates; loads parallel to web*

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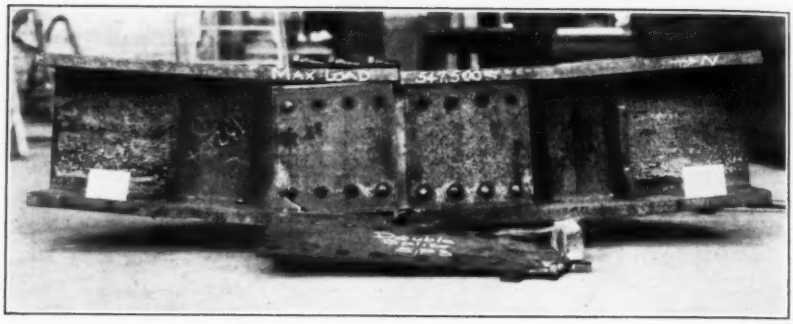

FIGURE 12.—*Specimen 4 after transverse test with outside splice plates removed; 14-inch* H *sections; double splice plates; loads parallel to web*

Welded plates failed along lower line of bolts; welds sheared; bolts started to shear.

FIGURE 13.—*Specimen 6 after transverse test with lower splice plate removed; 12-inch* H *sections; double splice plates; loads perpendicular to web*

Welded plates failed in bearing on bolts and sheared lengthwise; welds failed near ends.

V. ANALYSIS OF DATA

1. STRESS

The stresses in the specimens were computed using the common or Euler-Bernoulli theory of beams. Although the use of this theory for these specimens is open to a number of objections which will be discussed later, the data at hand did not warrant the use of a more refined theory. The computed stresses in the different parts of the specimens are given in Table 1. The analysis of stress will be explained for specimen 4 to show how the computations are made.

With equal loads applied at the quarter points of the beam as shown in Figures 7 and 14, the bending moment is constant between the loads and equals the product of one-half the total load and one-fourth of the length of the span. The maximum bending stresses occur at the section through one of the group of holes nearest the middle of the span. (Fig. 14.) Here the H sections are not effective in carrying tensile stress and the area of the splice plates is reduced because of the

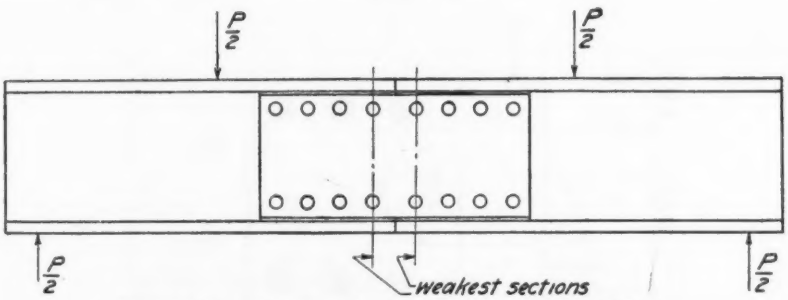

FIGURE 14.—*Diagram showing forces acting on the beam*

bolt holes. This section will be referred to as the "weakest section" of the beam.

The maximum bending stress in the splice plates and the H sections at the weakest section of the beam is given by the formula

$$S=\frac{Mc}{I} \tag{1}$$

in which

S is the maximum bending stress in tension or compression (lbs./in.^{2}),

M is the bending moment at the section (lbs.-in.),

c is the distance from the neutral axis to the extreme fiber in tension or compression (in.), and

I is the moment of inertia of the effective cross section (in.^{4}).

At the weakest section the splice plates act as beams. The upper part is in compression and the lower part is in tension with the neutral axis as the line of zero stress. The H section does not here act as a beam since there is no way in which it can carry tensile stress. The compressive stress varies from a maximum in the outer fibers to zero along some axis lower in the H section. The gravity axis of the areas assumed to carry stress was taken as the neutral axis. Included in the area effective for carrying compressive stress is a

small portion of the web of the H section lying between the neutral axis and the upper flange. Its effect on the position of the neutral axis and the value of the moment of inertia is small. Its effect on stress values is less than 2 per cent. Because of the shorter and simpler computations which resulted, this area has been neglected.

The portions of the specimens which are assumed to carry stress at the weakest section are shown by full lines in Figures 2 to 5. The portions above the neutral axis are in compression and those below the neutral axis are in tension. The portion indicated by dash lines do not carry stress at the weakest section. The area of the bolt holes was deducted for all splice plates except the upper plates on specimens 5, 6, and 7.

After computing the location of the neutral axis (gravity axis), the magnitude of the moments of inertia and the maximum tensile and compressive stresses, the reactions between the splice plates and the bolts must be determined before the stresses in the bolts can be obtained. For the specimens having the splice plates vertical, Figure 15 shows the part of the splice plates on one side of a sec-

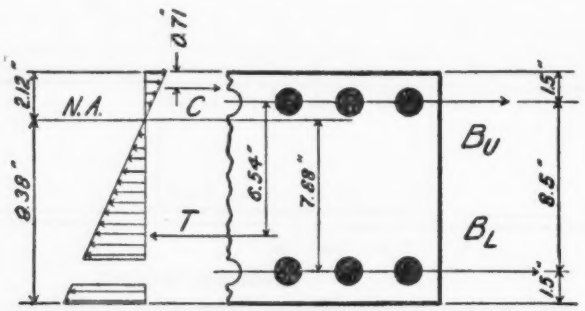

FIGURE 15.—*Free-body diagram showing forces acting on a splice plate*

tion through the inner group of bolt holes and also the forces acting on it. The forces are the stresses on the cut sections and the reactions of the bolts on the plates. There are no vertical forces, since the shear in the beam is zero between the loads. The frictional forces between the splice plates and welded plates are indeterminate and have been neglected.

Let C = the resultant compressive force on the upper portion of the plates. It acts at the third point of the distance between the top of the plate and the neutral axis.

In computing C, for specimen 4 at the maximum load, the compressive stress at the upper edge of the splice plates from formula 1 is

$$S_c = \frac{4{,}516{,}900 \times 2.12}{583} = 16{,}420 \text{ lbs./in.}^2.$$

The average stress is $\frac{16{,}420}{2} = 8{,}210$ lbs./in.^{2}.

The total area above the neutral axis for the four splice plates is $4 \times \frac{7}{16} \times 2.12 = 3.70$ square inches.

$$C = 8{,}210 \times 3.70 = 30{,}400 \text{ pounds}$$

Let T=the resultant tensile force on the lower portion of the plates. The stress on the outer fiber has been found to be 72,700 lbs./in.^{2} The stress at the axis of the holes is then $72{,}700\times\frac{7.88}{9.38}=61{,}100$ lbs./in.^{2} As no stress is transmitted across the portion of the section through the bolt holes, $T=\frac{1}{2}\times 72{,}700\times 9.38\times 4\times\frac{7}{16}-61{,}100\times\frac{15}{16}\times 4\times\frac{7}{16}=496{,}800$ pounds.

The arm of T about the neutral axis, as found by taking moments about the neutral axis, is:

$$\frac{\left[\left(\frac{72{,}700}{2}\times 9.38\times\frac{7}{16}\times 4\right)\times\frac{2}{3}\times 9.38\right]-\left[\left(61{,}100\times\frac{15}{16}\times\frac{7}{16}\times 4\times 7.88\right)\times 7.88\right]}{496{,}800}=5.92 \text{ inches.}$$

The reactions of the bolts, B_L and B_U, may now be found from the principles of statics for parallel forces. To find B_L take moments about the line of action of B_U.

The arm of T about $B_U=5.92+0.62=6.54$ inches.

The arm of $C=1.50-0.71=0.79$ inch.

$\Sigma M=0$ $B_L\times 8.5-496{,}800\times 6.54-30{,}400\times 0.79=0.$

$B_L=385{,}000$ pounds.

$\Sigma F=0$ $B_U+30{,}400+385{,}000-496{,}800=0.$

$B_U=81{,}400$ pounds.

B_U, therefore, acts in the same direction as B_L and C.

There are eight bolts in double shear on each side of the joint so the area in shear is $16\times 0.60=9.60$ in.^{2} The average shearing stress in the lower bolts is:

$$S_s=385{,}000\div 9.60=40{,}100 \text{ lbs./in.}^2.$$

The area in bearing is $8\times\frac{7}{8}\times\frac{7}{16}=3.06$ in.^{2} The average bearing stress in the lower bolts and the welded plates in contact with these bolts is:

$$S_c=385{,}000\div 3.06=125{,}800 \text{ lbs./in.}^2$$

To determine the forces, W_L and W_U, acting on the welds, consider the welded plates shown in Figure 16 in equilibrium under the known reactions of the bolts and the unknown forces acting at the welds. The forces are parallel and the values of the unknown forces may be found from the conditions that $\Sigma F=0$ and $\Sigma M=0$.

$\Sigma M=0$ $W_L\times 12.40-385{,}000\times 10.45-81{,}400\times 1.95=0.$

$W_L=337{,}300$ pounds.

$\Sigma F=0$ $W_U+337{,}300-385{,}000-81{,}400=0.$

$W_U=129{,}100$ pounds.

The length of weld on both plates is $2 \times 12 = 24$ inches. The average shearing stress in the lower welds is:

$$S_{sw} = 337{,}300 \div 24 = 14{,}100 \text{ lbs./lin. in.}$$

The computations for finding the stresses in the bolts and welds of specimens with loads parallel to the web are somewhat laborious.

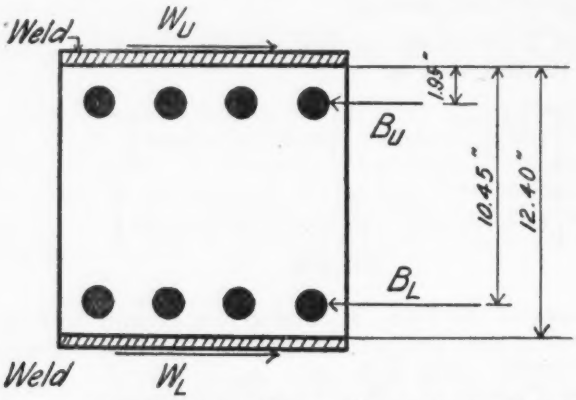

FIGURE 16.—*Free-body diagram showing forces acting on a welded plate*

An alternate method which involves one additional approximation may be used. It is shorter, and the results are probably as accurate as the data warrant.

The free-body diagram of a part of one H section together with the plates welded to it is shown in Figure 17. The H section is assumed to be cut at a point between the ends of the welded plates and the

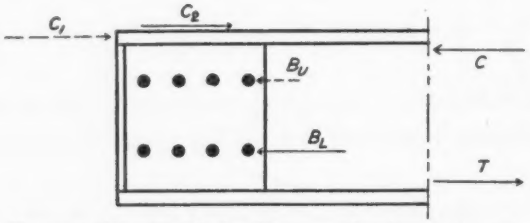

FIGURE 17.—*Free-body diagram showing forces acting on a welded plate and a portion of an* H *section*

C_2 is the resultant of C_1 and B_U.

applied load so that the bending moment at the cut section is equal to the constant moment in the middle half of the beam. The forces acting across the cut section are the bending stresses in the beam. These vary from zero at the neutral axis to a maximum at the extreme fiber. The compressive and the tensile forces may be replaced by their resultants C and T. These constitute a couple whose moment is equal to the bending moment in the beam. The other forces acting on the free body are the bolt reactions, B_U and B_L, and the reaction between the ends of the two H sections, C_1. If C_1 and B_U

are replaced by their resultant C_2, a second couple consisting of C_2 and B_L is obtained. This couple balances the couple consisting of C and T and, therefore, its value is also equal to the bending moment in the beam. By computing values for different positions of C_2 it has been found that C_2 may be assumed to act along the outside face of the upper flange for specimens similar to the ones included in these tests.

The values of B_L may now be found by dividing the bending moment by the distance of B_L from the upper face of the specimen. For specimen 4, at the maximum load,

$B_L = 4{,}516{,}900 \div 11.70 = 386{,}000$ pounds.

$S_s = 386{,}000 \div 9.60 = 40{,}200$ lb./in.^{2}.

$S_c = 386{,}000 \div 3.06 = 126{,}200$ lbs./in.^{2}.

The forces acting on a part of one H section without welded plates are shown in Figure 18. Replace C_1 and W_U by their resultant C_3

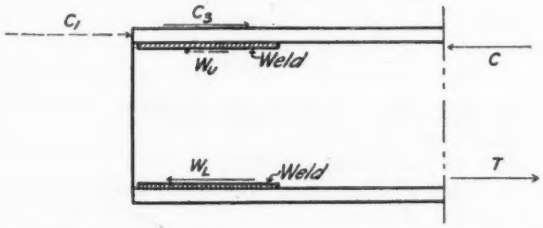

FIGURE 18.—*Free-body diagram showing forces acting on a portion of an* H *section*

C_3 is the resultant of C_1 and W_U.

acting along the outer face of the upper flange. The arm of the couple consisting of C_3 and W_L is 13.65 inches.

$$W_L = 4{,}516{,}900 \div 13.65 = 331{,}000 \text{ lbs.}$$
$$S_{sw} = 331{,}000 \div 24 = 13{,}800 \text{ lbs./lin. in.}$$

The values of the stresses in the bolts and in the welds of specimens 1 to 4 computed by both methods explained above are given in Table 2. The values by the second method agree closely with those computed by the first method. In all but three cases the difference is on the side of safety and in these cases the difference is less than 4 per cent.

TABLE 2.—*Comparison of stresses computed by different methods*

Specimen	Method	Maximum shearing stress in lower row of bolts	Maximum bearing stress of lower bolts and plates	Maximum shearing stress in lower welds
		Lbs./in.^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}
No. 1	First	30, 400	55, 500	5, 420
	Second	31, 300	57, 300	5, 230
No. 2	First	33, 000	120, 500	11, 500
	Second	33, 200	122, 000	11, 150
No. 3	First	39, 800	62, 300	7, 170
	Second	41, 000	64, 200	7, 050
No. 4	First	40, 100	125, 800	14, 100
	Second	40, 200	126, 200	13, 800

In general, the method of computing the value of the stresses in the specimens with loads perpendicular to the web are the same as those for the specimens with loads parallel to the web. (See specimen 5, fig. 4.)

Dividing the total tension in the lower plate by the areas of the bolts in shear and in bearing and by the length of the welds in shear gives the average stresses to which they are subjected.

2. DEFLECTION

Each of the dash lines in Figures 8 and 9 represents the deflection of a beam of constant cross section loaded at the quarter points and having a moment of inertia numerically equal to that of the computed value of the moment of inertia at the weakest section of the corresponding test beam.

This deflection is given by the formula

$$y=\frac{11Pl^3}{768EI}$$

in which y is the deflection at midspan (inches)
P is the total load (pounds)
l is the span of the beam (inches)
E is the modulus of elasticity (lbs./in.^{2}) and
I is the moment of inertia (in.^{4})

VI. DISCUSSION

1. METHOD OF ANALYSIS

The formula, $S=\frac{Mc}{I}$, should preferably be used to compute bending stresses in a beam only when the beam is long compared with its cross-sectional dimensions, the beam is constant in cross section throughout its length, and the bending stresses are below the proportional limit of the material. In these specimens the span of the beam was about five times the greatest cross-sectional dimension, which is below the values for which the common beam theory is applicable. There was a marked change in cross section at the splice, and the beams were loaded to failure.

The use of the beam formula for ultimate loads was analogous to its use in finding the modulus of rupture. Stresses computed from the ultimate load may be expected to hold closely for other specimens of the same size, shape, and loading, and approximately for those of similar size, shape, and loading. They should not be used as a basis for the design of widely different types of connections without further test.

For abrupt changes of cross section, such as occur in the neighborhood of the weakest section, there is no assurance that proportionality of stress to strain exists as was assumed in computing the bending stresses from their distance from the neutral axis determined according to the assumptions made in the analysis.

As the limit of proportionality of deflection to load was fairly definite for these specimens, the stresses corresponding to the "yield-

point" loads can probably be used for design purposes because these stresses in the various parts of the spliced connection correspond to the maximum deflection to which the splice should be subjected. The stresses corresponding to the maximum loads are also given since these loads caused known changes in the specimens and the computed stresses serve as a criterion for determining the value of the analysis.

In developing a method of analysis which can be used in the design of details with complex stress distribution, assumptions such as these may give results that differ widely from the actual stress conditions in the specimen. Nevertheless, the analysis can be used in design if it gives values of stress which are consistent; that is, if for any type of failure the values of stress computed for specimens that failed are higher than those which were computed for specimens which did not fail. An ultimate value of stress for design of similar connections may then be set which is below the values at which failure occurred in the tests. In this investigation the stresses at which failure occurred were, with one exception, greater than the corresponding stresses at which there was no failure. For the exception, the difference in the value of stress is less than 5 per cent. Moreover, the computed values at which failure took place are equal to or slightly above the ultimate strength of structural steel in tension, shear, and bearing so that these ultimate values may be used in designing similar connections.

2. STRESS

(a) H SECTIONS

The values of the compressive stresses in the H sections were low due to the short distance between the neutral axis and the extreme fibers.

(b) PLATES

Specimens 1, 2, and 7 failed by rupture of the splice plates in tension at computed stresses of from 68,600 to 83,200 lbs./in.^{2}. These computed stresses exceed the probable ultimate strength of the material in tension. A design based on an ultimate tensile strength of structural steel of 65,000 lbs./in.^{2} with a proper factor of safety should result in a splice of adequate strength in tension.

In two other instances the plates did not have sufficient strength to resist the stress to which they were subjected. The plates in specimen 5 bowed up as has been explained. In specimen 6 one welded plate sheared lengthwise. Based on the net area of a section through the bolt holes the shearing stress in this plate was 45,800 lbs./in.^{2}. It is evident that in the design of a connection the strength of the plates should be computed to insure that they will not fail as in specimens 5 and 6.

(c) BOLTS

The bolts in specimen 3 sheared at a computed stress of 39,800 lbs./in.^{2}. In specimen 4, in which the splice plates failed in bearing, the bolts had commenced to shear at a computed stress of 40,100 lbs./in.^{2}. These values are probably somewhat in excess of the ultimate strength of rough bolts in shear. For purposes of design this may be taken at 32,000 to 35,000 lbs./in.^{2}.

Four bolts in specimen 5 sheared at a computed stress of 35,000 lbs./in.^{2}. The splice plate and welded plates on the lower side of this specimen bowed up. This produced shearing stress in the bolts at right angles to the shear considered in the analysis. The value of the resultant shear may well have been in the neighborhood of those shown by the other specimens that failed in shear. The fact that not all the bolts sheared favors this explanation since the bending of the plates with consequent transverse shear increased toward the middle of the splice plate.

Signs of failure in bearing in the splice plates occurred at average bearing stresses of 109,000 to 125,800 lbs./in.^{2}. Designs of similar joints on the basis of allowable stresses of 90,000 to 100,000 lbs./in.^{2}. in bearing for structural steel should give splices of adequate strength.

In addition to shear and bearing, the bolts are also subjected to bending. In computing the bending stress in pins in pin-connected structures it is customary to assume that the loads on the pins are concentrated loads acting along the center line of the surface of contact. Since the thickness of the plates is only a small part of the arm of the forces, this method gives results which are sufficiently accurate. If the same method were used to compute the bending stress in the bolts in these specimens, relatively large errors would be introduced, since the moment arm of the forces would equal the thickness of one plate.

An exact analysis of the problem is not possible nor is it necessary. The bolt may be considered as a continuous beam on elastic supports under distributed load. The bending stress under such conditions will evidently be much less than if the same load is considered as concentrated and acting on a simple beam. Moreover, the effect of the nut on the bolt will be to reduce the bending, due to the loads applied to the bolt by the plates. Because of the uncertainty of any assumptions concerning the distribution of the loads on the bolts and on account of the absence of any definite indications of failure due to bending, no attempt has been made to analyze the bending stress in the bolts.

(d) WELDS

Several welded seams of specimen 4 failed at a computed stress of 14,100 lbs./lin. in. after the maximum load on the specimen had been reached. The welds of specimens 5 and 6 failed for a short distance at the ends at average computed stresses of 7,000 to 11,800 lbs./lin. in., respectively. These weld failures were due to local concentration of stress at the ends of the welds after the specimens had begun to fail elsewhere. The computed weld stresses are, therefore, not indicative of the full strength of the welds. In no case did failure of the specimens begin in the welds. Welds designed according to the provisions of the code for fusion welding in building construction formulated by the American Welding Society should be adequate in strength.

3. DEFLECTION

Figures 8 and 9 show that the load-deflection curves begin to deviate from a straight line at low values of load. This would indicate that portions of the connections were subjected to relatively high stresses at low loads with consequent redistribution of stress in the connections.

For specimens with loads parallel to the web there is a fairly close agreement between the observed values of deflection and

the computed deflection of a beam similarly loaded and having a moment of inertia throughout its full length equal to that computed for the weakest section of the splice of the actual beam. The ratio of this moment of inertia to that of the H section varied from 0.13 to 0.30. There is no assurance, however, that this agreement would hold for other lengths of span and methods of loading or for other ratios of moments of inertia. For specimens with loads perpendicular to the web, the actual deflection of the specimens was from 50 to 100 per cent greater than that of beams with a constant moment of inertia equal to that of the splice. The ratio of the moment of inertia at the weakest section of the splice to that of the H section varied from 0.56 for the 14-inch H section of specimen 7 to 1.03 for specimen 6.

4. COMBINED LOADING

In an actual structure the column connections are not only subjected to bending stresses, but are also called upon to assist in transferring direct loads from one column to another. The relative magnitude of the stresses due to direct load and bending will depend among other things on the size and shape of the building and the position of the column in it. In these connections, considered as simple beams, the maximum compressive stresses are small. Considering the column under the action of both types of loading, the compressive stress becomes of major importance and the column may be expected to fail in compression before the ultimate strength of the connection in bending is reached.

The splice will also be subjected to forces which cause bending and shearing of the splice. Transverse shearing of the splice is resisted by the frictional force developed between the ends of the columns and by the shearing stress developed in the splice plates. When the direction of the forces causing shear is perpendicular to the plane of the splice plates, local bending in the plates and tension in the bolts may also be produced. The stresses thus developed should be considered in connection with those caused by bending of the splice.

VII. CONCLUSIONS

The conclusions formed from tests of steel columns consisting of H sections 3 feet long and 10, 12, and 14 inches wide, connected with splice plates bolted to plates welded between the flanges of the H sections, and tested as simple beams with equal loads at the quarter points of a 66-inch span are:

1. The analysis of stress in these specimens using the simple beam theory gives maximum stress values in the connections which are consistent with the ultimate strength of structural steel.

2. Similar column splices having adequate factors of safety may be designed by these methods on the basis of the values of stresses prescribed by standard building codes for structural steel.

WASHINGTON, September 13, 1929.

ENGINE-IGNITION SHIELDING FOR RADIO RECEPTION IN AIRCRAFT

By H. Diamond and F. G. Gardner

ABSTRACT

The use of highly sensitive receiving equipment on aircraft has made the problem of airplane engine ignition shielding an important one. Ignition shielding consists of so confining the electrical fields of the ignition system that no interfering signal can be set up in the radio receiving circuits. The problem in ignition shielding is chiefly in the electrical and mechanical design of the arrangement for shielding, it being much more difficult to secure an assembly which will not adversely affect the engine-ignition system than to obtain complete freedom from interference for the radio equipment.

The bureau has been in active cooperation with airplane-engine, magneto, spark-plug, and cable manufacturers in an effort to develop a safe method for effecting this shielding and to make the necessary equipment available commercially. As a result of this cooperation shielding assemblies may now be purchased for use on all Wright and Pratt-Whitney airplane engines. A metallic ignition manifold is employed with high-tension cable drawn through it in the usual way. The leads from the manifold to the spark plugs and the groups of leads from the manifold to the magneto outlets are inclosed in liquid-proof flexible aluminum tubing with copper braid on the outside to insure effective shielding. Each flexible tubing is suitably fitted to the ignition manifold and to the magnetos or spark plugs, as the case may be. The magnetos are provided with covers which completely inclose the distributor blocks. A single outlet permits the use of an elbow fitting for connection to the large flexible metal tubing. This elbow fitting differs for different types of engines. Outlets are provided in the elbows for the booster and ground leads. The spark plugs are of a type in which the shield is an integral part and are provided with elbows for connection to the smaller flexible metal tubing. The ignition switch is totally inclosed in a metal cover, the booster magneto is also covered, and the leads from the magnetos to the ignition switch and booster magneto are inclosed in flexible metal tubing. The complete assembly insures electrical safety; mechanical sturdiness; liquid proofing of magnetos, spark plugs, and ignition cable; and ease of installation and of servicing.

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I. INTRODUCTION

The increasing use of radio reception on aircraft for weather and navigational services has made the problem of airplane engine-ignition shielding of primary importance. To obtain full efficiency of operation of the sensitive aircraft receiving sets now available, it

is necessary to eliminate the intense electrical disturbances set up in the radio-receiving circuits by the engine-ignition system. Ignition shielding consists of so confining the electrical fields of the ignition system that no interfering signal can be induced in the radio circuits.

The care which must be taken in ignition shielding depends entirely upon the ratio of the interfering signal of ignition [1] induced in the receiving antenna to the radio signal required. This ratio is dependent upon the sensitivity of the receiving set employed, the type and location of the receiving antenna, and the frequency of the signal to be received. The more sensitive the receiving set, the smaller is the signal voltage required in the antenna for actuating whatever device may be connected in the receiver output. Since the voltage of the ignition interference is fixed for a given antenna, the interference-to-signal ratio is thus increased. On the other hand, assuming a fixed receiver sensitivity (hence, a fixed minimum useful received signal) the interference-to-signal ratio will depend upon the length of receiving antenna and its position with respect to the interfering source. Finally, since the source of disturbance consists essentially of a group of spark transmitters of varying high frequencies, the higher the frequency to which the receiving system is tuned, the greater will be the interference-to-signal ratio.

Within the past two years it has become common practice to use a vertical pole antenna with a highly sensitive receiving set for reception on aircraft. The requirements for ignition shielding have, therefore, become rigorous. To obtain effective shielding it becomes necessary to inclose the entire electrical system of the engine ignition in a high conductivity metallic shield. Therefore, the magnetos must be provided with such metallic covers as will completely inclose the distributing heads. The booster magneto must also be inclosed in metal. All distributing wires must be covered with a metal tube or braid. The spark plugs must be completely shielded. The booster leads, the leads to the ignition switch, and the ignition switch itself, must also be shielded.

II. REQUIREMENTS FOR A PRACTICABLE SHIELDING ASSEMBLY

The inclosure of the high voltage electrical system of the ignition in a closely surrounding grounded metallic casing introduces certain problems of electrical and mechanical design. It is much more difficult to secure an arrangement which will not adversely affect the engine-ignition system than to obtain freedom from ignition interference for the radio equipment. The factors which enter into the design of a safe and practicable shielding assembly may well be stated at this point.

1. Reliability of engine performance is the first consideration. The shielding must be such as to prevent insulation breakdown of any of the component parts of the ignition system. Full provision for the protection of the component parts from the effects of oil, gasoline, and water should be made. Mechanical protection of the ignition cable and other parts is necessary.

[1] Where the engine is unshielded.

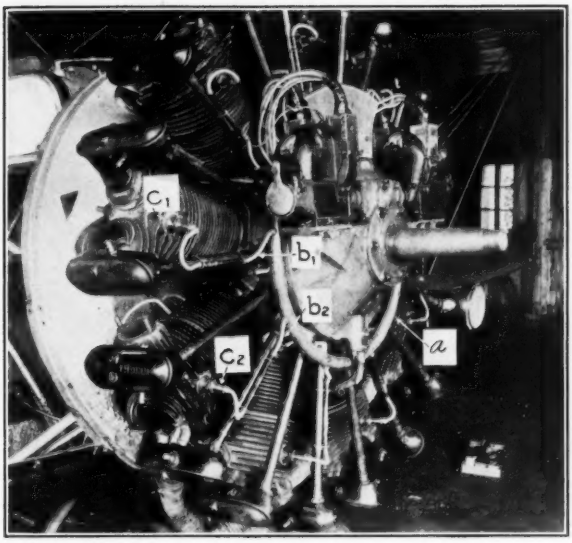

FIGURE 1.—*Early shielding installation on Wright J–5 airplane engine*

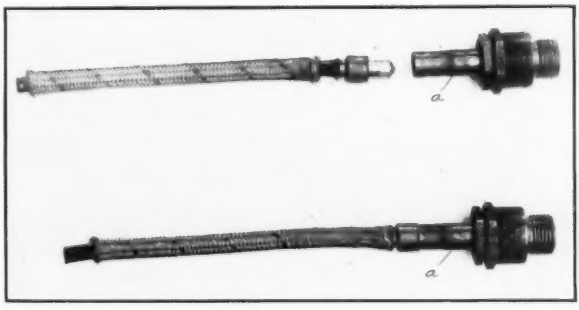

FIGURE 2.—*Early type shielded spark plug*

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2. Shielding of an effective and permanent nature is next in importance. The effectiveness of the shielding should not decrease with service. This requires a mechanically sturdy assembly.

3. The shielding assembly must be satisfactory from an operating point of view. Servicing of the spark plugs and magnetos should be possible with a minimum of effort on the part of the operating staff. Replacements of individual leads or groups of leads should also be possible. Ordinary replacements should in no way affect the efficiency and completeness of shielding.

4. In addition to the above considerations, it is important that the component parts of the shielding be simple in their manufacture in order that the cost of radio shielding shall not be prohibitive.

This paper describes the experimental work carried on at the Bureau of Standards toward the development of a satisfactory and safe shielding assembly. Active cooperation was maintained in this problem with other Government departments, with manufacturing concerns and research organizations in the aircraft and radio industries, and with several air-transport companies. The final shielding assembly shown in Figures 17 to 21, inclusive, which gives promise of fulfilling all the requirements for safe shielding, is a result of this cooperation.

III. DESCRIPTION OF BUREAU'S WORK

The bureau first became interested in the problem of ignition shielding in the winter of 1926–27, during the course of experiments on 2-way radiotelephony between aircraft and ground. However, the airplanes used in these experiments were equipped with water-cooled Liberty engines and little difficulty was had in shielding these engines, a satisfactory shielding arrangement having already been developed by Army Air Corps engineers. Owing to the shape of this type of engine and of the cowling employed, shielding of the spark plugs was not required. A few months later, when it became necessary to provide shielding for transport airplanes equipped with radial-type air-cooled engines, the situation was found to be entirely different. It became apparent that the price which would have to be paid for the use of receiving sets having the necessary sensitivity to make a vertical pole antenna feasible, was the screening of the spark plugs. Moreover, such work as had previously been done on the shielding of radial-type engines had resulted in shielding installations hardly practicable for use on commercial transport airplanes. The bureau undertook to develop a suitable shielding assembly.

1. EARLY SHIELDING ASSEMBLIES

Several experimental installations were made in order to determine specifically the amount of shielding necessary and the nature of the technical difficulties encountered. The installation shown in Figure 1 (on a Wright J–5 engine) represents the first one considered at the time sufficiently practicable for transport use. For the purpose of mechanical protection of the high tension distributing leads, the original ignition manifold (a) (supplied with the engine) was retained. Each distributing lead (b_1, b_2, etc.) was separately shielded with closely woven copper braid and threaded through the manifold. The method

of connecting the distributing leads to the shielded spark plugs (c_1,c_2, etc.) may be seen in Figure 1 and in somewhat better detail in Figure 2. Figure 1 also shows the method employed for shielding the magnetos. The distributor blocks were individually covered with metal cans accurately fitted to the magneto castings to within 0.005 inch. Hand-made covers using thin copper sheeting were employed in order to obtain a closer fit to the irregular magneto surfaces than was possible with the cast aluminum covers commercially available at the time. (See fig. 3.) The shielded spark plugs used were of a type developed jointly by the Navy Department and the B. G. Spark Plug Corporation, the shield being incorporated as an integral part of the spark plug. These were adopted only after considerable experimental work with metal covers for screening the plugs. Two types of shielding covers (figs. 4 (*a*) and (*b*)) were employed in the preliminary experimental installations with successful results in so far as radio shielding was concerned. However, totally inclosing the spark plugs had resulted in their operation at temperatures in excess of normal.

To obtain effective shielding it was found necessary to inclose the ignition switch in a shielding can, as shown in Figure 5. Covering the terminal block of the booster magneto and shielding the switch and booster leads by means of closely woven copper braid completed the installation.

From a radio point of view, the shielding installation as described above was satisfactory. Not the slightest trace of ignition interference could be heard in the head telephones when using a receiving set having an over-all voltage amplification of about 1,000,000 to 3,000,000. Practical difficulty was, however, experienced with this assembly. The magneto and spark plugs were not sufficiently protected from water. Short-circuiting of the spark plugs and of the magneto distributors during rain occurred. Furthermore, the over-all assembly was too frail mechanically. The method of connecting the distributing leads to the spark plugs introduced sharp bends in the leads exactly at their points of greatest exposure. Oil and dirt collecting on the metal braid at these points rendered the braid brittle. Whipping of the leads in the propeller slip stream resulted in breaks in the braid and in consequent decreasing effectiveness of shielding as well as in potential points of insulation breakdown.

Finally, the shielding assembly was faulty from the point of view of electrical design. Each lead being individually shielded, the capacitance per lead was from 400 to 500 $\mu\mu$f as compared with 80 to 100 $\mu\mu$f for the lead unshielded. While a capacitance of 400 to 500 $\mu\mu$f will not normally affect the magneto voltage sufficiently to interfere with the engine ignition, this is not necessarily true under certain abnormal conditions. Again, breaking of the small wires of the shielding braid, either in manufacture or in use, served to destroy the lacquered finish on the surface of the high-tension cable and produced points of brush discharge due to the interior current of the cable. The abrasive action of the metal braid on the cable also tended to injure the lacquered finish. This finish is necessary to protect the rubber of the cable against corona ozone that otherwise tends to rapidly destroy the rubber. The same film of lacquer protects the rubber against the effects of oil and moisture. With the lacquered film injured, faulty ignition occurred. The method of insulating the lead-in wires to the shielded spark plugs was also found to be unsatisfac-

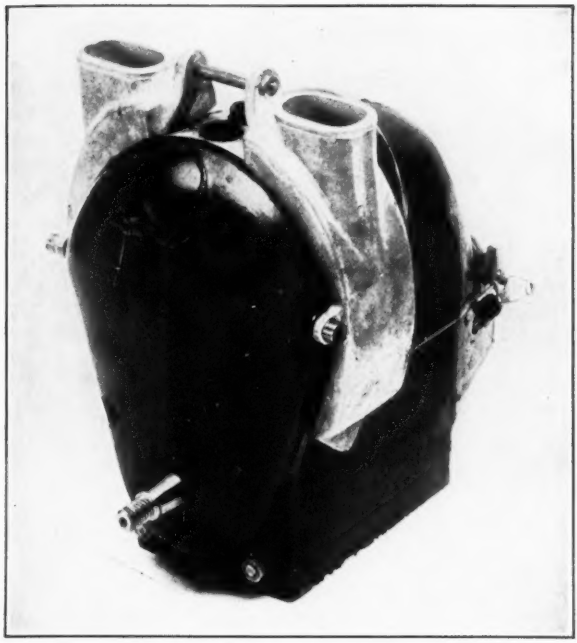

FIGURE 3.—*Early type shielded magneto*

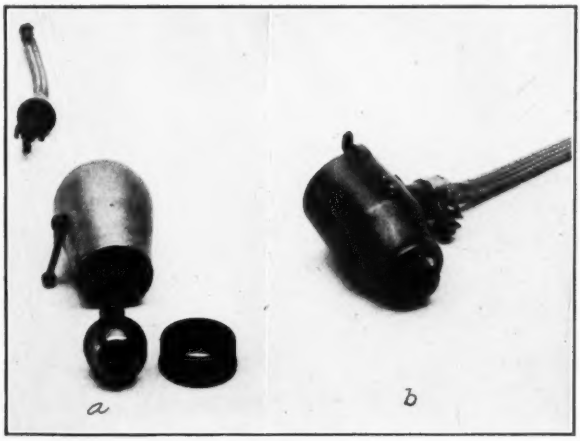

FIGURE 4.—*Metal covers for shielding spark plugs*

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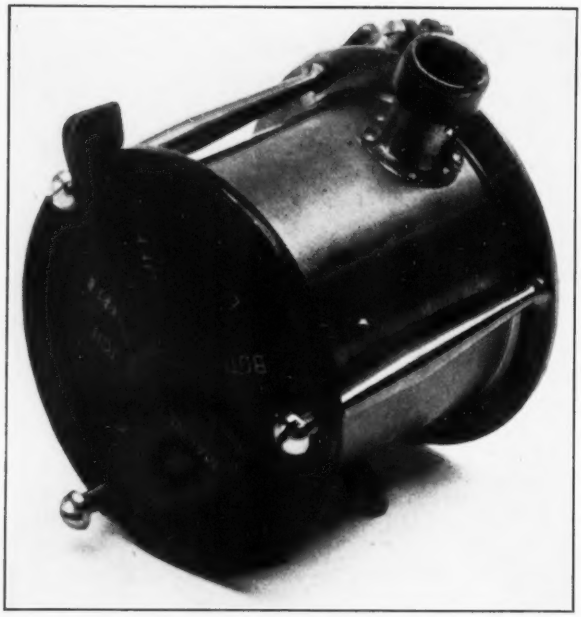

FIGURE 5.—*Completely shielded ignition switch*

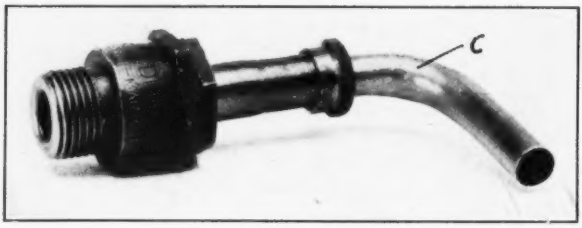

FIGURE 6.—*Shielded spark plug provided with elbow fitting to insure liquid proofing*

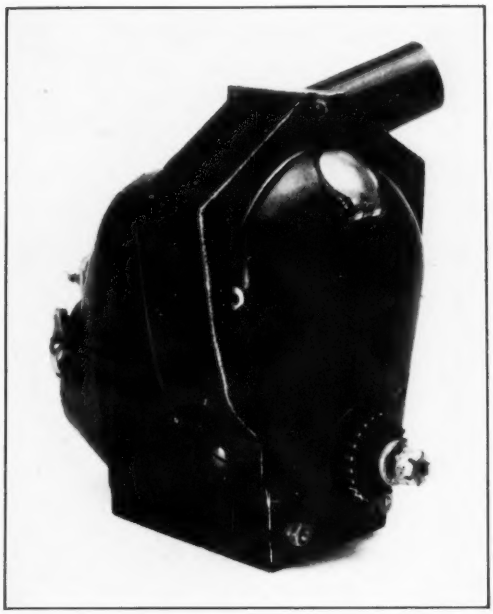

FIGURE 7.—*Completely shielded magneto with single outlet for the ignition distributing leads*

Liquid proofing is assured by this arrangement for shielding.

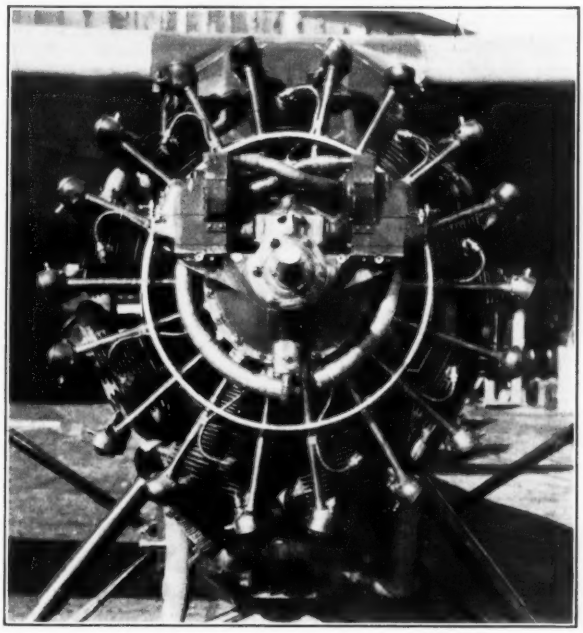

FIGURE 8.—*Early shielding installation on Wright J–5 airplane engine*

A special shielded ignition distributing harness is here employed.

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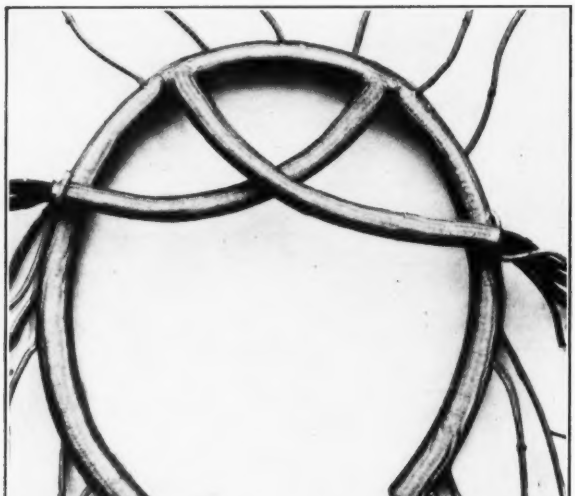

FIGURE 9.—*Shielded ignition distributing harness used in installation of Figure 8*

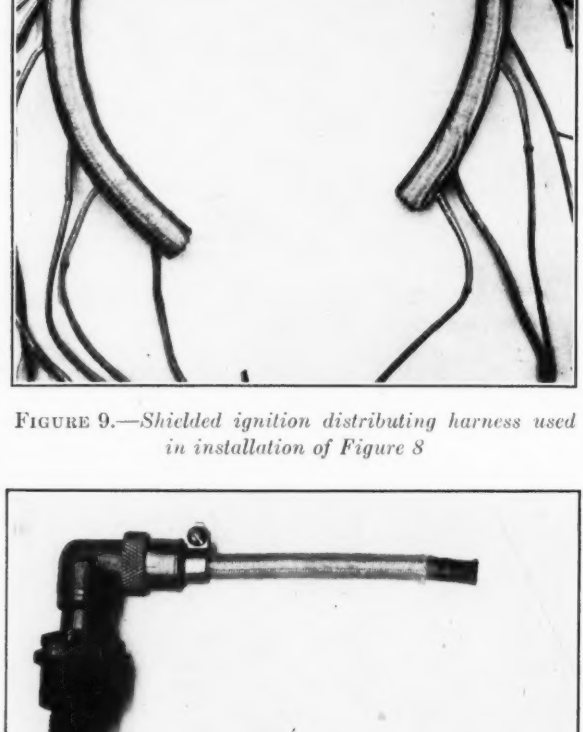

FIGURE 10.—*Elbow type shielded spark plug used in installation of Figure 8*

tory. Thin mica sheeting rolled in the form of cigarette tubes serve as an insulating wall within the metal stem (*a*) of the spark plug. (See fig. 2.) Flaking of the mica when taking the plugs apart for installation or inspection resulted in short circuits to the metal wall of the stem.

To provide better protection against rain for the spark plugs and magnetos, the arrangements indicated in Figures 6 and 7 were adopted. The aluminum elbow (*c*) Figure 6, was flanged so that with the knurled nut screwed tight, sealing of the spark plug against moisture was effected. The elbow also served as mechanical protection for the ignition leads at their points of maximum exposure. Whipping of the leads in the propeller slip stream was thereby prevented. The magneto distributing heads (fig. 7) were totally inclosed, a single outlet being provided for the nine ignition distributing leads. In addition to providing complete liquid proofing, this also served to improve the shielding of the booster and switch leads.

Simultaneously with this development, a second shielding installation was made on the bureau's experimental airplane (also equipped with a Wright J–5 radial-type air-cooled engine). A photograph of this installation is shown in Figure 8. A complete ignition harness (see fig. 9) developed through the cooperation of the Belden Manufacturing Co. was employed with the leads grouped together in a common ring. The nine leads to each magneto were also grouped. A closely woven copper shielding braid surrounded each group of wires, liquid-proof loom being used as a cushioning fabric between the groups of wires and the copper braid. Braiding the individual leads from the ignition harness to the spark plugs was still employed. The grouping of the leads and the use of shielding braid around the groups rather than on individual leads relieved considerably the added dielectric stress on the ignition cable due to shielding. It also served to decrease the capacitance to ground of each ignition lead, an average value of 160 $\mu\mu$f per lead being obtained as compared with 400 to 500 $\mu\mu$f per lead in the other type of installation.

The shielded spark plugs used were of an improved type, the B. G. Spark Plug Corporation having modified their early design in order to incorporate the features found essential in the bureau's tests. A photograph of the new design (showing also the method of connecting the ignition lead) is given in Figure 10. The cross-sectional diagram of Figure 11 shows the details of assembly. The feature of right-angle entrance of the ignition lead was found very satisfactory from an installation and maintenance viewpoint. It was made possible, however, only after considerable experimental work on the part of the manufacturer, the provision of continuous insulation within the elbow proving particularly difficult. The type of shielded magneto employed is shown in Figure 12. For convenience in installation, the single outlet for the nine distributing leads was brought out on the side rather than on top of the shielding cover.

While this second shielding assembly proved somewhat more durable in service than the first type described, the wire braid over the portions of the ignition cable from the shielding harness to the spark plugs continued to be a source of trouble. The braid acted like a wick to hold oil or water and to lead it along the cable to the spark plugs. Sealing the spark plugs against moisture proved difficult. Moreover, the oil being held in contact with the rubber

insulation of the cable rapidly deteriorated the rubber (whenever the lacquered film was broken). Faulty ignition then occurred. It was found necessary to replace the ignition harness after only 30 hours of operation. By winding oil tape over the shielded wire (see fig. 13), the life of the second harness was increased to about 50 hours.

The necessity for replacing the complete ignition harness because of faults developing in several leads demonstrated that it was economically unsound to use an assembly of this type. It became evident that an important requirement for a shielding assembly was that the individual leads should be readily replaceable. It was also apparent that some method of shielding the individual leads from the

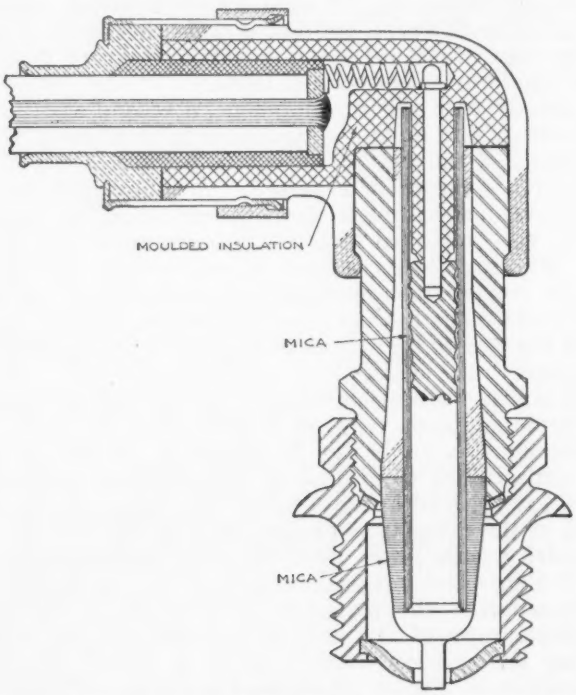

FIGURE 11.—*Cross section of elbow type shielded spark plug*

ignition manifold to the spark plugs other than by the direct application of metal braid over the high-tension cable was necessary.

2. IMPROVED SHIELDING ASSEMBLY, MANIFOLD TYPE

At about this time a cooperative program on ignition shielding was begun with the Wright Aeronautical Corporation, the Pratt-Whitney Aircraft Co., and the Breeze Corporations. The engineers of these companies were in agreement with the conclusions drawn from the bureau's experiments. A joint study of the situation resulted in the shielding installation shown in Figure 14. A metal manifold ring was employed, with unshielded high-tension cable drawn through it in the usual way. To complete the shielding of the ignition leads from the manifold to the spark plugs, each lead was inclosed in a

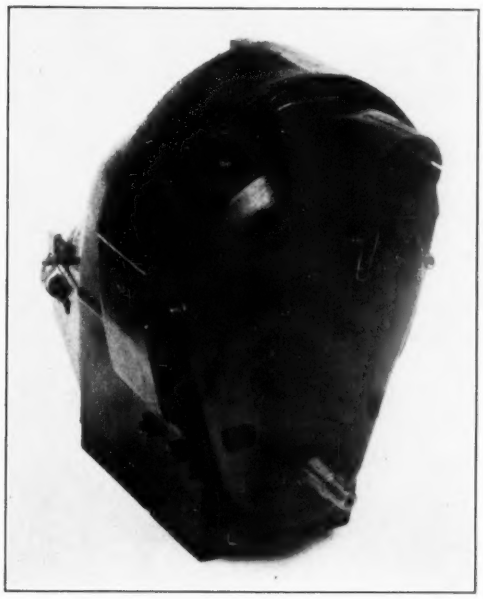

FIGURE 12.—*Completely shielded magneto used in installation of Figure 8 with side entrance for the ignition distributing leads*

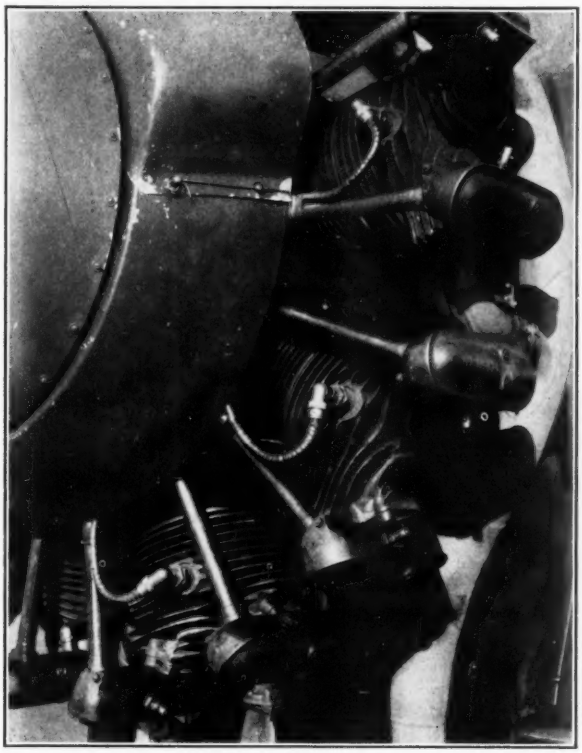

FIGURE 13.—*Photograph showing the method used in the installation of Figure 8 for protecting the ignition leads against the effects of oil, water, etc.*

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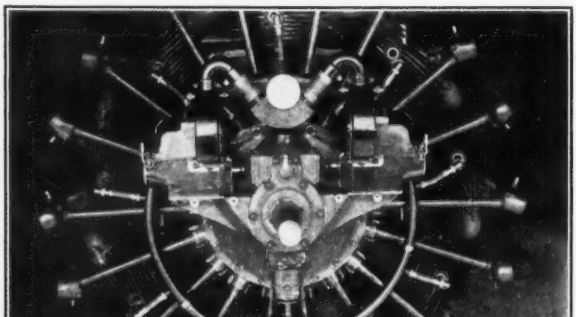

FIGURE 14.—*Improved shielding installation on Wright J–5 airplane engine*

Flexible metal tubing is used for shielding the exposed portions of the ignition cable.

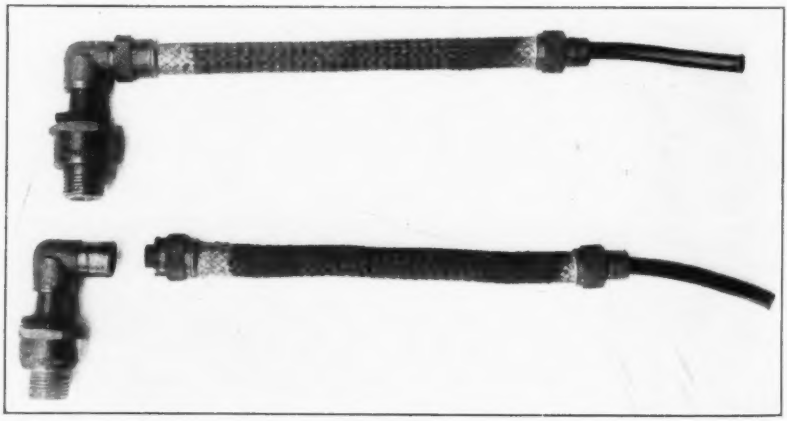

FIGURE 15.—*Arrangement for connecting the flexible metal tubing to the elbow type shielded spark plug*

liquid-proof flexible aluminum tube, which was provided with a threaded fitting at one end for attachment to the mainfold and with a cap fitting at the other end for attachment to the shielded spark plug. The groups of leads from the manifold to the magneto outlet were similarly inclosed in flexible aluminum tubing of proper size. This larger tubing was connected to the manifold through a suitable union box and to the shielded magneto by means of an elbow fitting. To insure efficient shielding, it was considered desirable to surround the flexible tubing with closely woven copper braid.

The shielded spark plug used was of the B. G. elbow type. The method of connecting the flexible aluminum tubing to the spark plug may be seen from Figure 15. Servicing of the spark plugs is obviously very easy.

The magneto shielding employed (see fig. 16) was developed through the cooperation of the Scintilla Magneto Co. The feature of complete liquid proofing, found desirable in the bureau's tests, was incorporated in this design. The irregular surfaces of the magneto which had made liquid proofing difficult in the experimental models (see figs. 7 and 12) were eliminated by the use of new castings, special grooves being provided in these castings to insure a liquid-tight joint for the shielding covers. A split shielding cover with an auxiliary elbow fitting was adopted, making possible the inspection of either distributor block without removing the cover from the other block. This also permitted the use of different shaped elbows to suit installations on different engines. The small outlets (a_1, a_2) for the leads to the booster magneto and the ignition switch were also split. An inspection of the magneto is thus possible without the necessity for disconnecting a single lead.

The use of flexible metal tubing was extended to the shielding of the booster and switch leads, the added mechanical protection for these leads being considered desirable.

The advantages of the manifold type shielding assembly described above are obvious. The assembly provides full mechanical protection for the component parts of the ignition system; liquid proofing of the magnetos, spark plugs, and ignition cable; and ease of installation and of servicing. The electrical design is also sound. The ignition cable is subjected to as low dielectric stress as is possible with a completely shielded system. The average capacitance per lead is comparatively small (180 $\mu\mu$f).

Two installations were made using this type of shielding, one on the bureau's experimental airplane and one on a transport airplane. Both gave very satisfactory service with not a trace of faulty ignition. On the transport airplane, special test flights were made during rain, and satisfactory operation was had.

The success obtained with the manifold type shielding assembly led to the commercial development of an assembly having the same fundamental design. Shielding for the Wright J–5 and J–6 engines and for the Pratt-Whitney Wasp engines has thus become commercially available. Several improvements over the bureau's design are of interest. Figure 17 is a photograph of the commercial product for a Pratt-Whitney Wasp engine. Note that the union box for connecting the large flexible metal tubing to the manifold ring has been eliminated. This removes the possibility of damage to the insulation of the ignition cable due to sharp edges. Note also that the elbow

fitting of the shielded magneto provides outlet for the booster and switch leads. This permits the use of the convenient arrangement shown in Figure 18 for shielding these leads. The shielded spark plugs shown in Figure 17, and in somewhat better detail in Figure 19, differ from the B. G. elbow type in the manner in which the insulation within the elbow is provided. Instead of molding the insulation within the metal elbow, a nickel-plated isolantite elbow is used. Either type of shielded spark plug may be employed in the assembly of Figure 17. Since weight is an important consideration in the design of equipment for aircraft, it is interesting to note that the weight added to the ordinary ignition assembly in order to provide complete shielding as well as liquid proofing is but 5 to 6 pounds.

Figure 20 shows the installation of a shielding harness of the commercial type on the bureau's experimental airplane, which is now equipped with a Wright J–6 engine. The shielding of the booster and switch leads is shown in Figure 21. The shielded ignition switch is not shown.

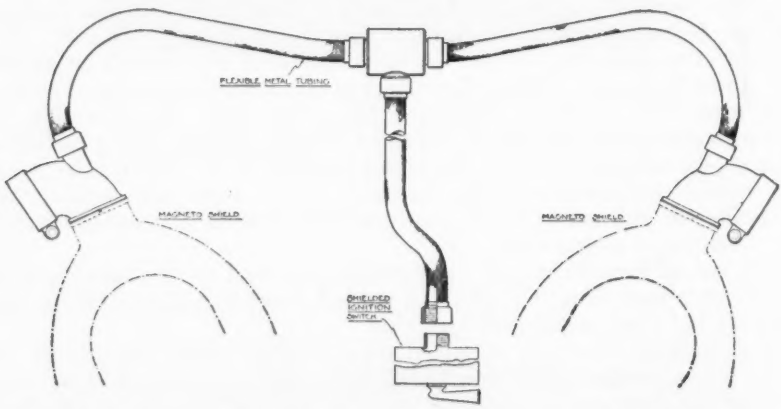

FIGURE 18.—*Diagram showing the use of flexible metal tubing for shielding the booster and switch leads*

IV. BONDING OF AIRCRAFT—SHIELDING OF AUXILIARY ELECTRICAL APPARATUS

Additional sources of disturbance exist on aircraft other than the engine-ignition system. Ineffective bonding of the airplane is often the cause of interference with the radio receiving apparatus. By bonding is meant the interconnection of all metal parts of the aircraft by means of electrical conductors. If bonding is not provided, noises may be produced in the radio receiver due to sparks occurring between two metal members having a difference of potential due to the collection of static charges. Varying resistance between rubbing or vibrating metal parts is also a cause of noises in the radio receiver.

Complete specifications for bonding are given in Technical Order No. 08–5–1, Office of the Chief of Air Corps, War Department, Washington, D. C.

A certain amount of noise in the receiving set output may result owing to commutator sparking of the generator used for battery charging or for supplying power to transmitting apparatus and

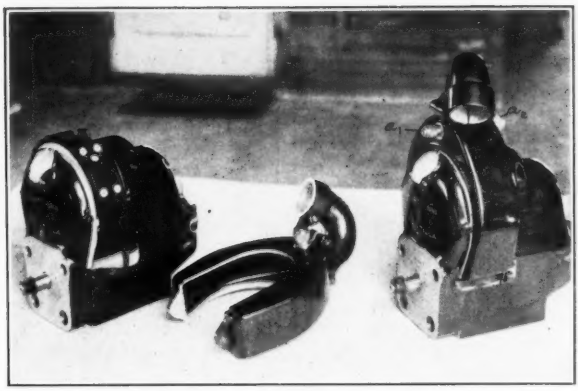

FIGURE 16.—*Completely shielded magneto with single vertical outlet for the ignition distributing leads*

A special elbow fitting is employed which may be varied to suit different installations.

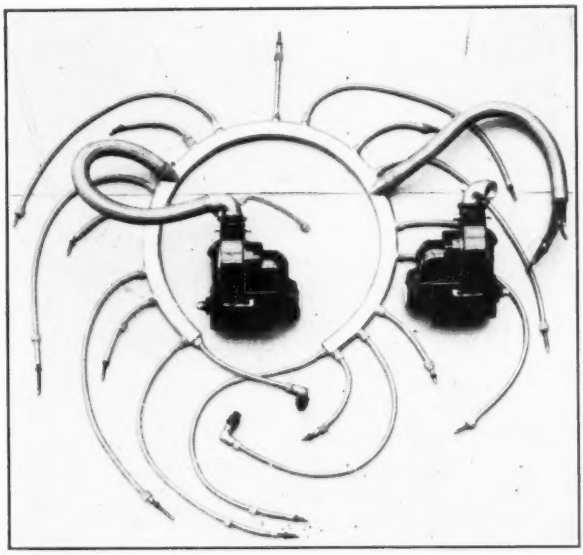

FIGURE 17.—*Commercial shielding assembly for Pratt-Whitney Wasp engine, patterned after assembly shown in Figure 14*

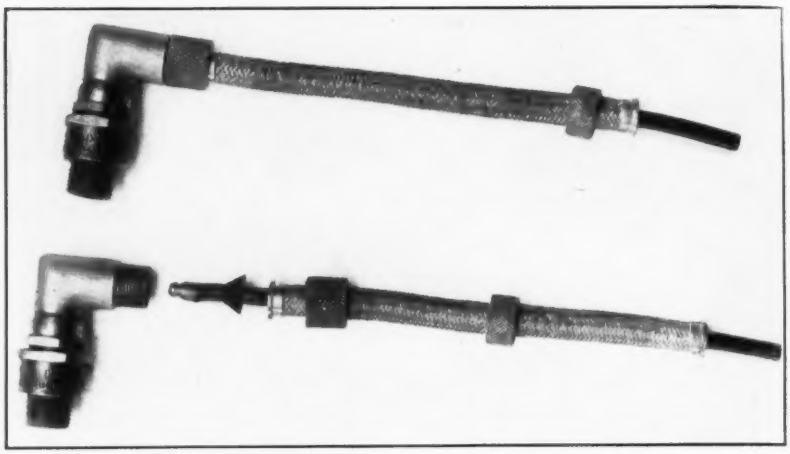

FIGURE 19.—*Elbow type shielded spark plug using nickel-plated isolantite elbow*

Note the arrangement for sealing the spark plug against moisture.

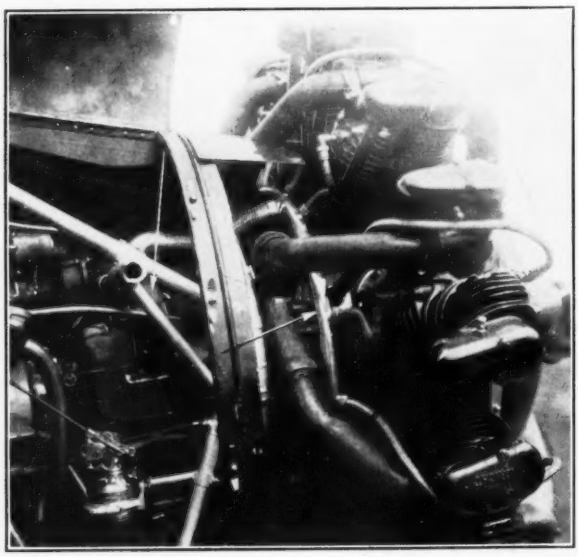

FIGURE 20.—*Installation of the commercial type shielding assembly on bureau's Wright J–6 airplane engine*

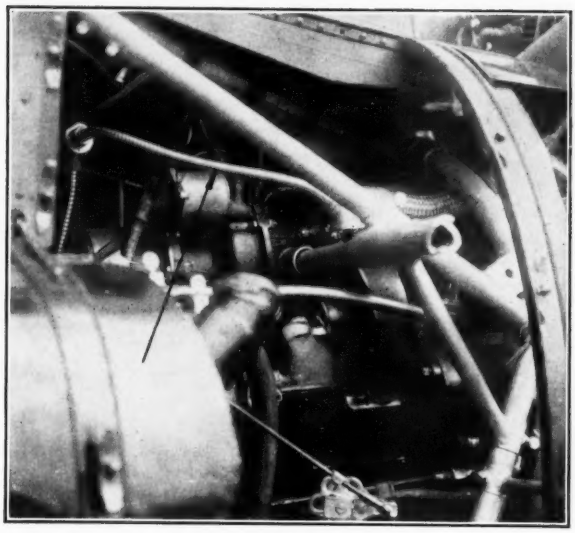

FIGURE 21.—*Arrangement employed for shielding the switch and booster leads*

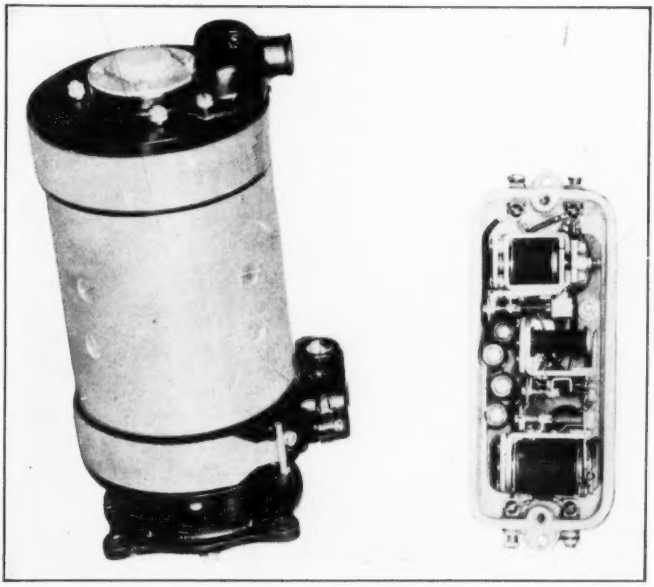

FIGURE 22.—*Completely shielded double-voltage generator and control box*

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receiving apparatus on aircraft. The sparking of the vibrating type voltage regulators used with these generators is an additional source of disturbance. Wherever possible, any piece of apparatus in which a spark occurs should be completely inclosed in metal. A photograph of a shielded generator and control box is given in Figure 22. Completely inclosing the generator is, however, not sufficient, since the disturbance may be carried by way of the leads from the generator. This requires shielding of all the leads. If the generator serves as a source of supply for the receiving equipment, suitable filter units must be employed in addition, to keep the commutator noises out of the radio receiver.

Further information on this subject may be obtained by reference to mimeographed notes [2] on the "Minutes of conference on airplane engine ignition shielding held at the Bureau of Standards, June 11, 1929." This conference was called by the Bureau of Standards in response to a number of requests from representatives of the aircraft and radio industries. The purpose of the conference was fourfold:

1. To coordinate the experience and knowledge of the numerous organizations interested in this problem.
2. To formulate the requirements essential to safe shielding.
3. To stimulate the standardization of shielding assembly practice.
4. To set up standard tests whereby the mechanical, electrical, and radio efficiency of a given shielding installation may be determined.

V. TESTS FOR PRACTICABILITY OF SHIELDING SYSTEM

It is to be emphasized that the manifold type of shielding assembly described in this paper is not necessarily the only practicable solution of the problem of ignition shielding. The problem may be approached from numerous angles, so that other solutions entirely as practicable are possible. For this reason a set of standard tests was tentatively adopted at the conference on ignition shielding whereby the practicability of any shielding assembly, no matter of what type, may be determined. These tests are outlined below. The usefulness of these tests is now under investigation.

1. TEST FOR SHIELDING

The best test for radio shielding is the actual use of the shielding assembly mounted on the airplane engine. The radio receiving set must be suitably installed on the airplane, with an antenna of at least 6 feet extending vertically above the fuselage, and must be adjusted to maximum sensitivity. The receiver should have an over-all voltage amplification of the order of 1,000,000 to 3,000,000. If the shielding is complete, no ignition noise should be heard in the headphones (connected in the output of the receiver) for all engine speeds and for all tuning adjustments of the receiver. In this test it is understood that the engine is functioning normally in every way (that is, spark-plug gaps properly adjusted, etc.), that the noise level in the receiving set output due to atmospheric disturbances is normal, and that the airplane itself is suitably bonded and all auxiliary apparatus, such as generators, voltage regulators, or any other circuit wherein a spark occurs, are effectively shielded.

[2] Copies of these notes may be obtained on application to the radio section, Bureau of Standards, Washington, D. C.

2. TEST OF COMPLETE ASSEMBLY FOR SPARKOVER

This test, together with the two following tests, should be made previous to installing the shielding assembly on the airplane engine. In this test the ignition leads are inclosed in the shielding manifold and terminate in the magneto distributor blocks with shielding covers at one end and in the shielded spark plugs at the other end. All connections between the component parts of the shielding assembly must be the same as when installed on the airplane engine. Provision should be made to ground the shielding assembly at points corresponding to grounds made when installed on the airplane engine. The magnetos are not used in this test in order to prevent damage to them. Mica insulators should be placed between the spark-plug points to prevent sparking at the test voltage to be employed. A voltage of 15,000 volts effective (of 60-cycle or higher frequency) should then be applied between all the ignition wires in parallel and the ground for a period of five minutes. Under this condition no sparking should occur. The condition of sparking may be determined by a sudden increase in the deflection of an indicating instrument connected in series with the above circuit. A regulating resistor is then also necessary to prevent burning out of this instrument.

3. TEST FOR INSULATION RESISTANCE DURING AND AFTER EXPOSURE

The same set-up as in the previous test shall be employed, except that the mica should be removed from the spark-plug gaps and provision made to protect the interior of the spark plugs from moisture. The complete assembly should be subjected to a spray of water for a period of three hours and readings of the insulation resistance of the individual leads to ground taken at intervals of one hour during this exposure. At no time should the insulation resistance of any lead to ground be less than 1 megohm.

4. TEST FOR CORONA

A suitable length of high-tension cable shielded in exactly the same way as the ignition leads extending from the main portion of the ignition manifold or casing to the spark plugs, and flexed at the least radius of curvature used shall be subjected to a voltage of 15,000 volts effective (60 cycles or higher in frequency) between conductor and shield for a period of two hours. Under this condition no sparking should occur.

WASHINGTON, October 9, 1929.

DEVELOPMENT OF THE VISUAL TYPE AIRWAY RADIO-BEACON SYSTEM

By J. H. Dellinger, H. Diamond, and F. W. Dunmore

ABSTRACT

Research work on a radiobeacon system for use on the airways of the United States has been under way at the National Bureau of Standards during 1926 to 1929. As a result of this work a system has been developed which fulfills the requirements for course navigation on the civil airways. A directive transmitter is employed on the ground, making possible the use of simple apparatus on board the airplane. A simple receiving set suffices to make use of all the radio aids provided. Visual indication is provided on the airplane instrument board by means of a tuned-reed instrument. The pilot observes the vibrations of two reeds. On the course the vibration amplitudes are equal. Off the course they are unequal, the reed vibrating with the greater amplitude being on the side to which the airplane has deviated.

Two types of beacon transmitters are described, the double modulation and the triple modulation. The former is capable of serving either 2 courses at 180° with each other or 4 courses at arbitrary angles. The latter serves 12 courses at any desired angles, and is adapted for use at any airport located at the junction of a large number of airways. Reed indicators for use with the double-modulation and triple-modulation beacons are described.

Descriptions are given of the receiving set and receiving antenna system developed. Airplane-engine ignition shielding is also discussed.

A marker beacon system has been developed whereby the pilot is given visual indication of his exact position at definite points along the route.

Special adaptations of the beacon system are being developed to facilitate landing in fog.

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I. INTRODUCTION

This paper gives a general description of the research on radiobeacon systems for the airways of the United States during 1926 to 1929. More specific descriptions of various features of the development are given in B. S. Research Papers Nos. 19, 28, 35, 77, 148, 154, and two now in press. The titles of these papers are given in references numbered, respectively, 15, 9, 22, 13, 12, 14, 10, and 21, in the bibliography (Sec. XI) at end of this paper.

The object of the research was to provide a system of navigational aids by which aircraft could be flown on a course in fog or any condition of visibility or no visibility. This system was to be specifically adapted to the requirements of navigation on the airways of the United States. The navigational aids developed have therefore had primarily in view the rendering of maximum service to fixed airways, the needs of aircraft on independent courses being secondary. Happily, as will be shown, the system evolved gives aid to the independent flyer as well as to the navigator of the regular airways.

The system furnishes a pilot the desired guidance without special maneuvers of the aircraft or more than ordinary attention on his part. All the complicated and expensive parts of the system are at ground stations maintained by the Government. The pilot is required to do nothing at all to obtain a reading but glance at an indicating instrument on his instrument board whenever he wishes.

1. THE NEED FOR THIS DEVELOPMENT

With the transportation of air mail, express, and passengers constituting its basic source of revenue, the success of air transportation in the United States depends in large measure upon the rigorous maintenance of scheduled flying by day and night. Present-day business requires the gathering of the mail at the close of a business day and its transportation to remote destinations for early delivery on the next or next following morning. The transportation of passengers by air can become a genuine service, and really popular, only when the traveler can count on a scheduled service as dependable as the railway trains and independent of weather or other contingencies.

The present limitation on this most essential feature of air-passenger service arises entirely from the hazards of the weather. Means are at hand to cope with every other limitation on flight. Multiple engines and improved controllability assure safety, landing fields are being provided in great numbers, aircraft of adequate strength and stability are available, and every comfort and convenience are

offered the air traveler. And yet air traffic is still halted when meteorological conditions make the pilot uncertain that he can see landmarks, lights, or landing field.

It is impossible to exaggerate the difficulties of a pilot flying in dense fog. Deprived of all landmarks, under incessant strain at the controls to maintain equilibrium and direction, the aviator must

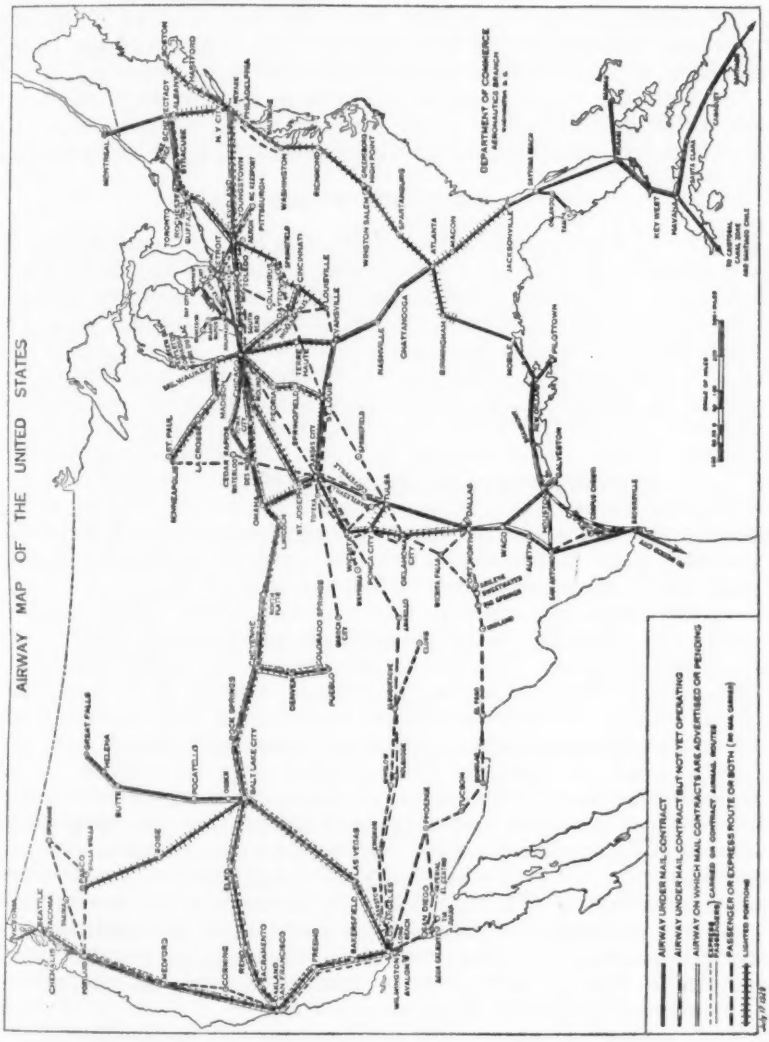
AIRWAY MAP OF THE UNITED STATES
DEPARTMENT OF COMMERCE
AERONAUTICS BRANCH
AIRWAY UNDER MAIL CONTRACT
AIRWAY UNDER MAIL CONTRACT BUT NOT YET OPERATING
AIRWAY ON WHICH MAIL CONTRACTS ARE ADVERTISED OR PENDING
PASSENGER OR EXPRESS ROUTE OR BOTH (NO MAIL CARRIED)
LIGHTED PORTIONS

FIGURE 1.—*Map of civil airways of the United States*

frankly abandon dependence upon his senses and navigate according to the information conveyed by his instruments.

By means of the familiar instruments, such as the altimeter, bank and turn indicator, rate-of-climb indicator, and compass a pilot can continue flying in fog, but it is only by radio means that he can be certain to keep on a given course and find his landing field when the ground is invisible. Accurate as a compass may be, it can not

tell the pilot how much he is drifting sidewise owing to cross winds, nor what actual progress he is making forward because of the unknown effects of head or tail winds. Unless radio aids are used fog always brings the hazard of getting off the desired course into unfamiliar or dangerous areas, and also makes even the possibility of a safe landing small.

By means of the radiobeacon system in its present form the pilot can keep accurately on his course, know the points he is flying over, and proceed unerringly to the landing field. Adaptations of the radiobeacon to the landing problem are now in progress which it is believed will also make possible landings in densest fog. With the system fully established a great obstacle to safe flight will have been conquered and additional dependability added to scheduled flying.

2. PREVIOUS WORK

The present development differs from much of the earlier work on radio navigational aids in its emphasis upon the requirements of fixed airways. The first work in this field was for military purposes in the World War. Military aircraft inherently require direction-determination service on independent courses. They do not generally fly fixed airways. The natural means chosen accordingly was the direction finder. The use of loop antennæ, with sensitive receiving sets, aboard (1)[1] airplanes, gave a homing device well adapted to military needs. This method has not been extensively used for nonmilitary aviation because of the great difficulties experienced with receiving apparatus of this type. It has the inherent limitation that it does not prevent wind drift from shifting the airplane off its course; the method does eventually bring the airplane to its destination, although by a circuitous route if there is a side wind.

The next chief development was also a direction-finder method, but with the direction finder located on the ground. This is the system (2) now used for aircraft navigation by radio throughout Europe. Every airplane in the commercial transport service carries a radiotelephone (or radiotelegraph) transmitter and receiver, used with a trailing-wire antenna. There are permanent direction-finding stations located at certain of the principal airports. When an airplane desires to learn its position, it transmits a telephonic request to the airport, whereupon two or more of the ground direction-finding stations each determine the direction by observations upon the radio waves transmitted by the airplane. Triangulation then gives the airplane's position, which information is transmitted to the airplane. The system requires the airplane to carry both transmitting and receiving apparatus. It is not effective when a large number of airplanes desire the position service simultaneously, as the ground station can serve only one airplane at a time.

A third method of furnishing navigational aid to the flyer is the rotating radiobeacon recently developed in England (3). This is a radio transmitting station, located at an airport, which has a directive antenna rotating at a constant speed of one revolution per minute. A figure-of-eight pattern is thus rotated in space. A special signal indicates when the figure-of-eight minimum passes through north

[1] The figures given in parentheses here and throughout the text relate to the reference numbers in the bibliography given at the end of this paper.

and also when it passes through east. A pilot listening for the beacon signal with his receiving set can start a stop watch when the north signal is received and stop it when the figure-of-eight minimum reaches him. The number of seconds multiplied by 6 gives him his true direction in degrees from north. The stop watch may be calibrated directly in degrees, so that the position of the second hand when the minimum signal is received gives the bearing directly. This system thus serves any course within its range. It has, however, the disadvantages of slowness of operation and also of being difficult to use during conditions of severe atmospheric disturbances or interference from outside services.

The radiobeacon system described herein is an outgrowth of a development undertaken by the Bureau of Standards for the Army Air Service in 1920. The Air Service requested the bureau to devise a method whereby a directional transmission would serve as a guide to airplanes along a chosen course. Such a method was developed (4) having the advantages that direction service could be given simultaneously to any number of airplanes flying the course, and that each airplane only had to carry a receiving set, with no other special equipment whatever. A description of this method, the subsequent contributions of the Army engineers, and the more recent work by the Bureau of Standards, follow. A discussion of the relative merits and features of the various types of radio navigational systems is given in Section IX.

II. THE AURAL RADIOBEACON SYSTEM

The radiobeacon system employs two directive antennæ placed at an angle with each other. Along the line bisecting the angle between the two antennæ, the intensities of the radio waves from the two are equal. Elsewhere, one of the two waves is stronger than the other. An airplane could, therefore, follow a course along the bisector referred to if the two sets of radio waves could be distinguished from one another. A different signal is impressed on each set of waves for this purpose.

In the original apparatus transmission took place alternately from the two antennæ, a switch being used to throw the radio-frequency power from one antenna to the other. Tests made at Washington on the ground and on ships showed that a course was effectively marked out and could be followed. The apparatus was next set up by the Bureau of Standards with the cooperation of Army engineers, at Dayton, Ohio, and tests made in the air. The method was successful in airplane flights and had the advantage that no error was introduced by wind drift, which is an important limitation on the use of direction finders aboard aircraft. For a discussion of this see page 294 of reference (4).

In the following four years the Army engineers at Dayton, Ohio, developed this radio range [2] further (5); in particular, they devised a signal-switching arrangement such that the signals from the two antennæ merged into a steady dash when on the course, giving an added criterion besides that of equal signal intensity to enable the observer to tell whether he was on or off the course. They also introduced a goniometer, or mutual inductance device, to permit

[2] A name which is coming into use for any directive radiobeacon transmitter.

orienting the course in any desired direction without moving the antennæ. The idea of interlocking the two signals to be compared was founded on an early German patent (6). The theory underlying the operation of the goniometer was also known (7). The contribution made by the Army engineers was to combine the two in a practical operating system.

The subject received renewed study by the Bureau of Standards early in 1926. There was pending in Congress a proposal to create an Aeronautics Branch in the Department of Commerce with jurisdiction over commercial flying and with the duty of providing aids to air navigation. The department officers requested the Bureau of Standards to recommend ways in which radio could be used for aids to navigation on the airways. In the recommendations submitted the bureau proposed the providing of telephone broadcasts of weather information to aircraft from ground stations maintained by the Government and a radiobeacon service of the type here described. It was pointed out that this would put all the expensive and heavy radio equipment on the ground, to be maintained by the Government, requiring the airplanes to carry nothing but a very simple receiving set.

Accordingly, when the Aeronautics Branch was organized, in July, 1926, it assigned the necessary experimentation and development in this field to its research division, which was organized in the Bureau of Standards. In the work on the radiobeacon, which began immediately, several improvements over the existing form of the beacon were sought. These included some matters of design detail (involving the goniometer, interlocking switch, etc.), an automatic device for serving several courses simultaneously (for use at airports where several courses intersect), and especially means of replacing the telephone receivers by a visual indicator. The work, which still continues, has been done in the bureau laboratory at Washington and at two field stations, one at College Park, Md., a suburb of Washington, and the other at Bellefonte, Pa., chosen because of its location on the New York-Cleveland airway in particularly hazardous mountain terrain. These two stations were equipped with radiobeacon and also radiotelephone and radiotelegraph transmitting apparatus. The Bellefonte, Pa., station was transferred in 1928 to the Airways Division of the Department of Commerce, and is now used for giving regular radio service to the portion of the transcontinental air route on which it is situated. The College Park station continues to serve as a development laboratory and as a model and demonstration station, and is, in addition, available to give radio service to the air routes passing through Washington. A photograph of this station showing the directive antenna system is given in Figure 2.

Experiments with different transmitting arrangements led to the adoption of that shown in Figure 3. Numerous test flights over a period of more than a year proved this circuit arrangement to be satisfactory. A 250-watt master oscillator supplies power to two 1 kw. power amplifiers, which in turn feed the two loop antennæ crossed at 90° with each other. A 4-coil goniometer is interposed between the power amplifiers and the antennæ to permit orientation of the beacon courses in any desired direction. Each primary winding of the goniometer, acting in conjunction with the two crossed secondary coils and the two crossed-loop antennæ, sets up a system which

FIGURE 2.—*Experimental radiobeacon station at College Park, Md., showing directive antenna system*

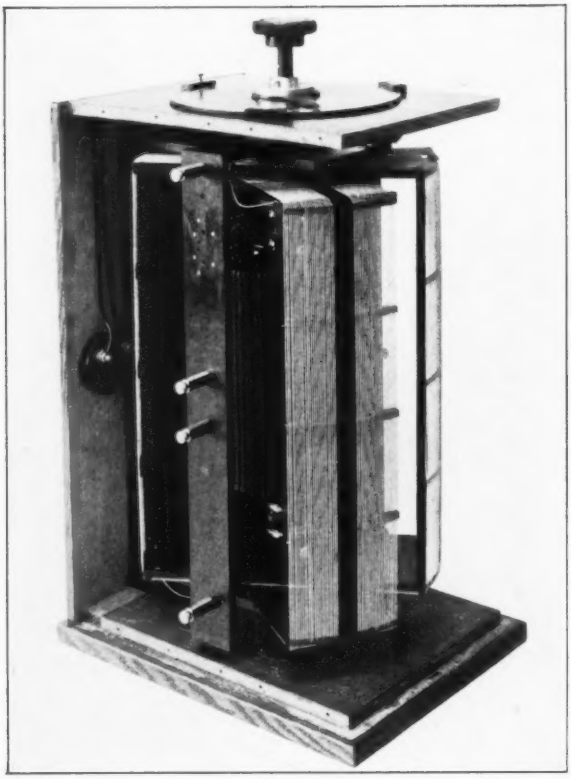

FIGURE 4.—*Simplified goniometer used in the circuit arrangement of Figure 3*

is electrically equivalent to a single-loop antenna. The plane of this phantom antenna is dependent upon the relative coupling of the secondary coils to the primary coil under consideration.

Since there are two primary windings, two such phantom antennæ exist, the angle between their planes being equal to the angle between the primary windings. The two phantom antennæ may be rotated in space (thus changing the position of the equisignal zones or courses formed by their space patterns) by changing the relative position of the primary windings with respect to the secondaries. This may be accomplished by rotating either the primary or the secondary coils. A photograph of the goniometer used in the transmitting circuit

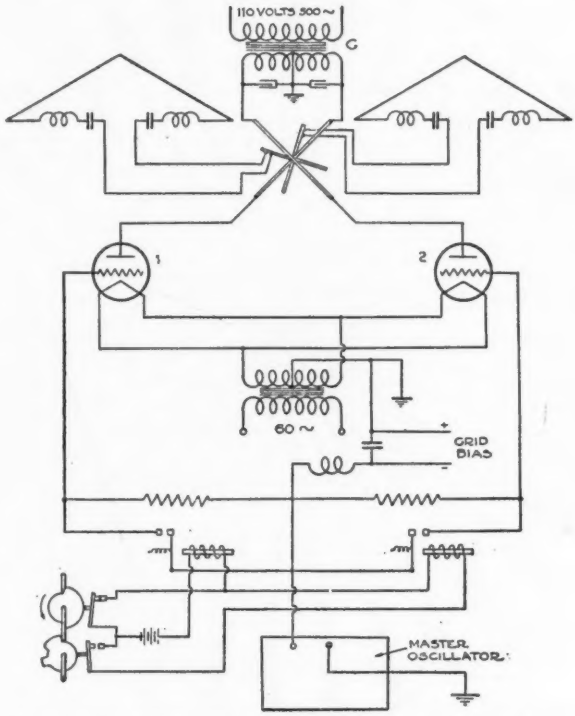

FIGURE 3.—*Improved circuit diagram of interlocking-signal type radio range*

arrangement of Figure 3 is shown in Figure 4. For convenience in mechanical construction the secondary coils are the ones capable of rotation. The primary coils are each of 32 turns of insulated wire and the secondary coils each of 8 turns of heavy litz wire.

The arrangement used for obtaining an interlocking signal is evident from Figure 3. As the cams rotate slowly, amplifier tube *1* is excited with the Morse letter *N* and amplifier tube *2* with the letter *A*. Phantom antennæ *1* and *2* are correspondingly excited. The two signals are so interlocked that an observer located on a line bisecting the angle between the two phantom antennæ (thus receiving signals of equal amplitude from both antennæ) obtains only long dashes. Were he not on this bisector line, he would receive a pre-

ponderance of either letter *A* or *N* depending upon his position with respect to the bisector. Figure 5 shows a diagrammatic representation of the interlocking signal for different angular positions around the beacon.

The goniometer shown in Figure 4 and the interlocking arrangement are both refinements over those used in the Army beacon. In the Army system the goniometer primary coils were usually of one or two turns and connected in a tuned circuit fed by the transmitter output, a cam-operated relay being provided to throw first one primary

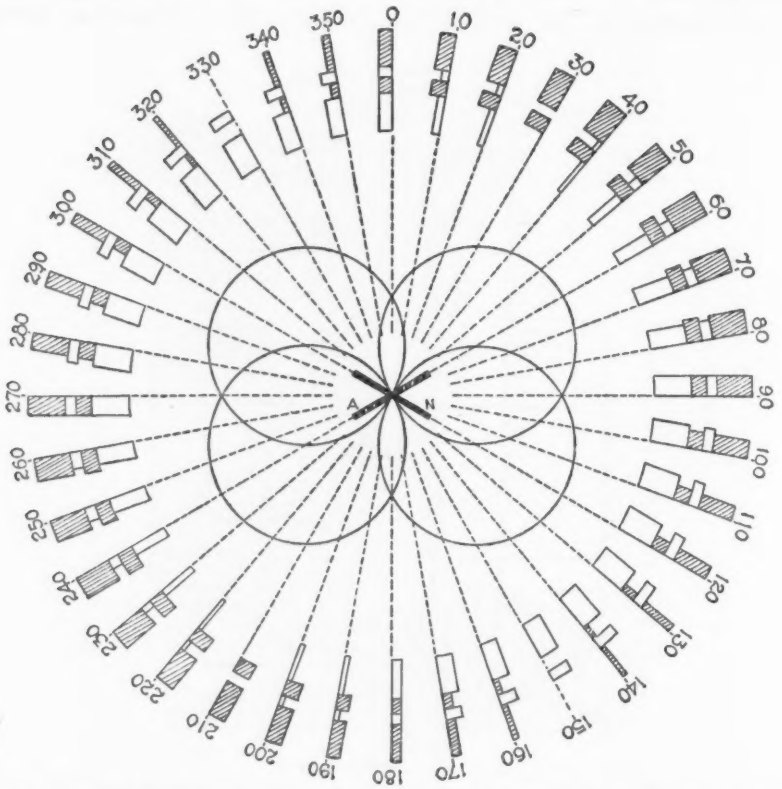

FIGURE 5.—*Interlocking characteristic of aural type radio range, showing change in relative intensity of the two signals received on an aircraft flying around the beacon*

and then the other in circuit in order to produce the desired interlocking signal. Interlocking, therefore, involved the breaking of heavy radio-frequency currents. In the circuit network of Figure 3 the interlocking is accomplished in the low-power side of the system, the relays controlling only the radio-frequency grid currents of the tubes.

It will be noted that tubes *1* and *2* never receive grid excitation simultaneously. This insures that the goniometer primaries are never excited simultaneously, and, in consequence, the angle between these primaries may be made of such value as to give the most useful beacon

space pattern. The pattern shown in Figure 5 is for a 60° angle between primaries.

Tone modulation of the transmitted signals is obtained by exciting the plates of all the transmitting tubes from a 500-cycle source. The self-rectifying method of exciting the power-amplifier tube plates adds considerably to the stability of the circuit network.

III. THE DOUBLE-MODULATION BEACON SYSTEM

1. FIRST EXPERIMENTS

A number of disadvantages are inherent in the aural interlocking radio range. Of these, the constant strain on the part of the pilot in listening to the guiding signals and distinguishing between their

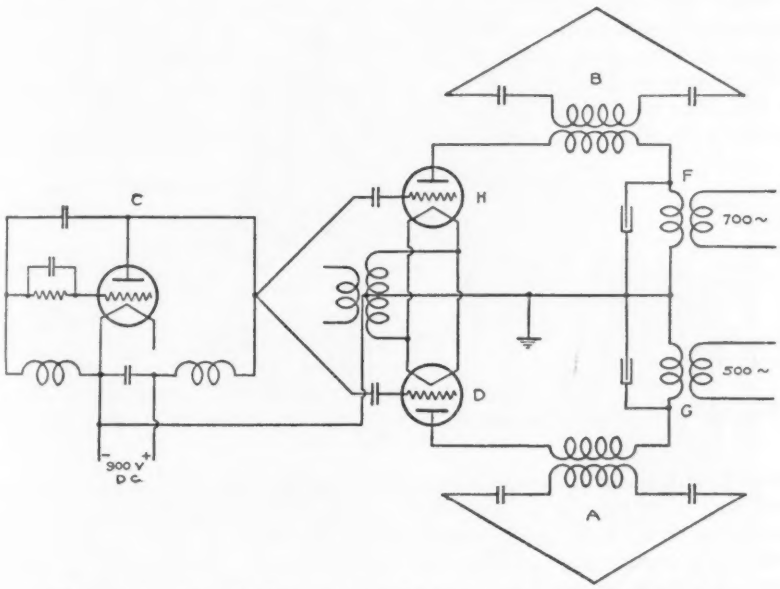

FIGURE 6.—*Circuit diagram of early type double-modulation beacon*

magnitudes is the most important. Another disadvantage is the masking of the guiding signals by atmospheric disturbances or interference from other services, with a consequent reduction in the effective distance of reception. A third is the skill required on the part of the pilot in interpreting the received signal.

The bureau, therefore, undertook the development of a visual means for receiving the guiding signals. A method devised in 1926 consisted of supplying both antennæ with radio-frequency power simultaneously, each supply being modulated by a different audio-frequency. The transmitting-circuit arrangement used is shown in Figure 6, and consists of a master oscillator supplying power to two amplifiers, which in turn feed the loop antennæ. A goniometer may be connected between the power amplifiers and the antennæ. The plate of one amplifier is excited from a 500-cycle source, and the plate of the second amplifier from a 700-cycle source. The receiving

circuit shown in Figure 7 serves to separate the two modulation frequencies by means of rejector circuits *FH* tuned to 500 cycles and *GI* tuned to 700 cycles, and selector circuits *K* and *L* tuned to pass 500 and 700 cycles, respectively. Tubes *N* and *G* rectify the output currents of the two transformers, the zero-center microammeter *0* being so connected as to indicate the difference between the rectified currents. An equisignal zone or "course" is evidenced by zero reading of this instrument, a deviation to the left or right of a given course causing a deflection of the instrument pointer to the side of deviation.

In an attempt to simplify the transmitting apparatus a second visual system was tried in which the two sources of audio-frequency were reduced to one. The two transformers (*F* and *G*, fig. 6) were replaced by a single transformer with the secondary center tap grounded and 500-cycle supply impressed upon the primary winding.

With this self-rectifying method of supplying plate voltage, radio-frequency current flows in only one antenna at a given time. An observer, exploring the field around a beacon station so connected, will encounter four narrow zones of 1,000-cycle pitch (corresponding to the four equisignal zones). At points 45° on either side of these 1,000-cycle zones the signal from but one loop antenna is heard. In

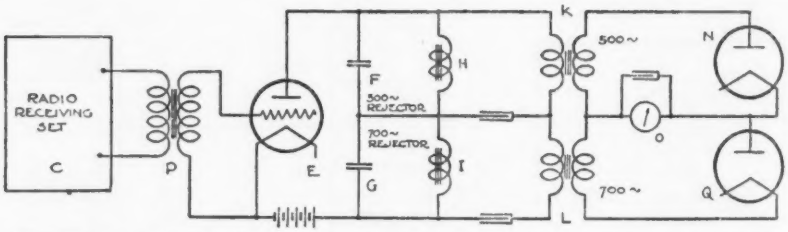

FIGURE 7.—*Circuit diagram for visual indicator using zero center microammeter*

these positions a 500-cycle note is obtained. If the observer moves from any 1,000-cycle zone toward either of the neighboring 500-cycle zones, he finds a location where the amplitude of the received 500-cycle note equals that of the 1,000-cycle signal. Eight such positions exist and may be used as beacon courses, the same receiving system as shown in Figure 7 being employed for indicating these courses, except that the circuits are tuned to 500 and 1,000 cycles instead of 500 and 700 cycles. Further information on this method, including a diagram showing the beacon space pattern, is given on pages 900 to 902 of reference (8).

While the above two systems of visual indication had some promise, both had the inherent disadvantage of being susceptible to errors due to interfering signals. There were also other disadvantages, such as complexity of apparatus and lack of positive indication when on course (since the beacon could be inoperative and the indicating instrument still read zero).

2. USE OF TUNED-REED INDICATORS

A method was then worked out which overcame these difficulties. Two low-modulation frequencies were employed, 65 and 86.7 cycles per second. The visual indicating instrument (9) for use on the

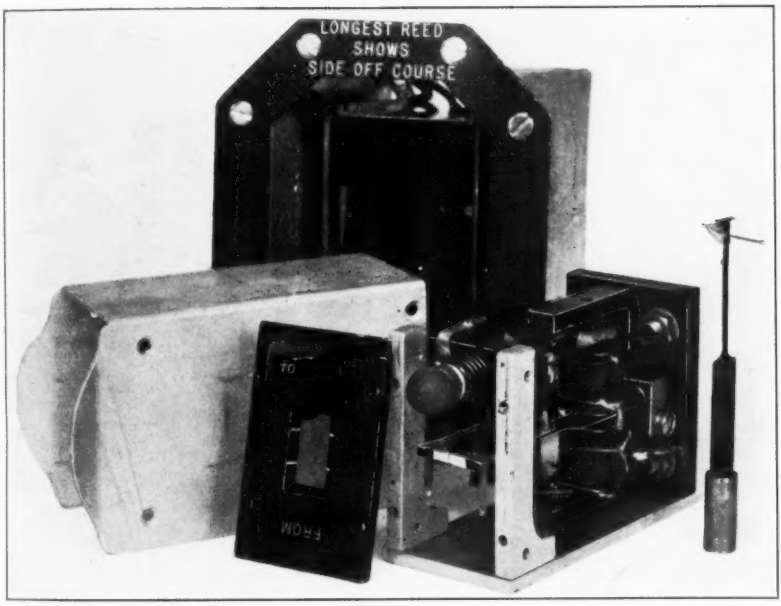

FIGURE 8.—*Visual beacon course indicator with shock proof mounting, 2-course type*

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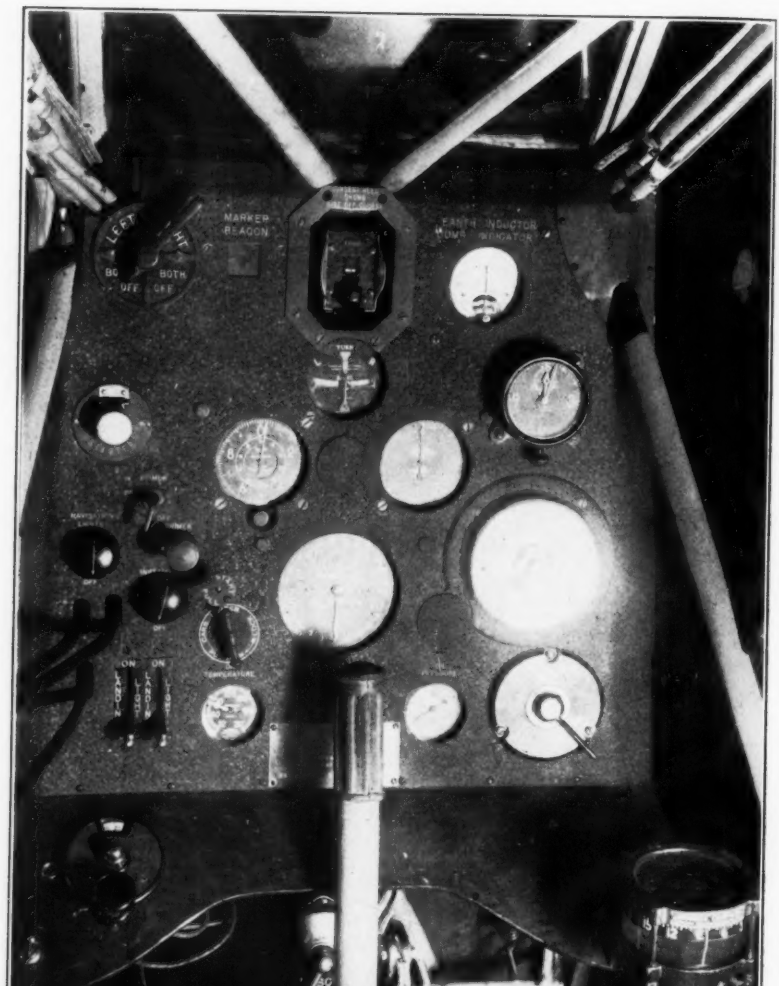

FIGURE 9.—*Airplane instrument board with course indicator mounted above the other instruments*

airplane consists of two vibrating reeds mechanically tuned to the two beacon modulation frequencies, actuated by small electromagnets connected to the output circuit of the receiving set. When the beacon signals are received, the two reeds vibrate, and, since they are tuned to the two modulation frequencies used at the beacon, serve as a device for indicating equality of received signals from the two antennæ. The tips of the reeds are white against a dark background, so that when vibrating they appear as vertical white lines. When the two lines are equal in length, the airplane is on its course. In the interest of simplicity, the adjustment is always such that a deviation from the course to the left serves to increase the relative deflection of the left reed, and the reverse is true if the airplane deviates to the right. To return to the course, the pilot turns in the direction of the shorter reed deflection. A photograph of the reed indicator with shock-proof mounting is given in Figure 8. Figure 9 shows this indicator installed on the instrument board of the bureau's experimental airplane.

Simplicity of operation has resulted from the use of this system. An ordinary receiving set with a small reed unit weighing less than an ordinary pair of headphones constitutes the airplane equipment. A signal is received whether on or off the course, a glance at the relative reed amplitudes being sufficient to tell the pilot whether or not he is on the course, and, if not, approximately how far off he is and to which side. Finally, the sharp mechanical tuning of the reeds adds the very desirable feature of freedom from interfering signals, the reeds operating effectively through interference sufficient to ruin aural reception.

A diagrammatic representation showing the relative deflections of the two reeds comprising the visual course indicator for different deviations in degrees from a given beacon course is shown in Figure 10. As may be observed, a deviation of $\pm 1°$ may be readily detected.

To make the use of the course indicator as simple as possible, a plug-in arrangement is provided so that the relative position of the two tuned reeds of the indicator may be reversed (by turning the indicator upside down). Reference to Figure 10 will indicate the purpose of this reversal. Suppose that a pilot is flying away from the beacon on either course *A* or *C*. If he deviates to the left of his course, the amplitude of the 65-cycle reed will increase and that of the 86.7-cycle reed will decrease. A deviation to the right of the course results in an opposite effect. It is desirable, therefore, to place the 65-cycle reed on the left of the 86.7-cycle reed in order that the pilot may observe the simple and instinctive rule (longest reed shows side off course—turn to the shorter reed). When flying to the beacon, however, this rule holds true only if the relative position of the reeds is reversed, the 65-cycle reed being now on the right of the 86.7-cycle reed. Consider, now, the two 90° courses, *B* and *D*. On these courses the relative position of the two reeds (in order to make the rule stated above apply) is exactly the reverse of that for courses *A* and *C*, whether flying from or to the beacon. To distinguish between the two sets of courses (*A*, *C* and *B*, *D*) a color system may be adopted on the airway maps, *A*, *C* being in one color and *B*, *D* in another. A shutter is mounted on the course indicator

front which exposes either one color or the other. When set to the first color the words [TO / FROM] are exposed, while when the shutter is set to expose the second color, the words [FROM / TO] are exposed. The pilot then sets the shutter to the color of the course to be flown and plugs in the course indicator in order that the direction (with respect to the beacon) which he is to fly is right side up. The simple rule stated above then obtains. A complete description of the shutter arrangement is given in a separate paper (10).

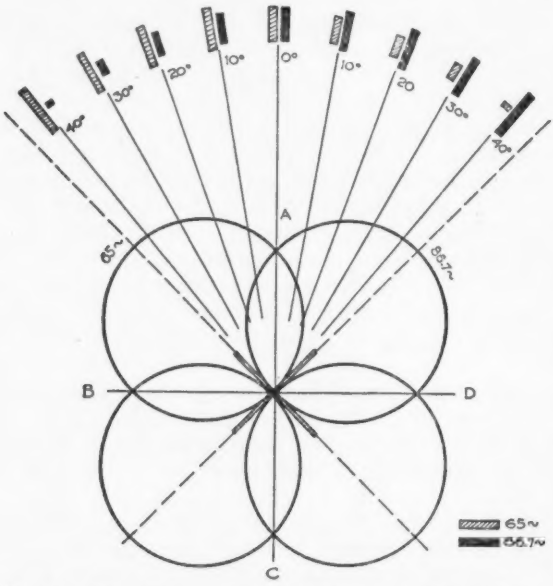

FIGURE 10.—*Space characteristic of double-modulation type radio range showing relative deflections of the two reeds comprising the course indicator for different deviations in degrees from the beacon course*

3. GENERAL DETAILS OF TRANSMITTING ARRANGEMENT

Since the vibrating reeds are sharply tuned to their particular frequencies, it is necessary that the modulation frequencies of the transmitter be kept constant within certain limits. In the earlier beacon transmitting arrangements (see fig. 11) this requirement was met by the use of electron-tube driven tuning forks mechanically tuned to the desired frequencies. The outputs from these tuning forks, after sufficient amplification, were made to modulate the 290-kc. carrier in the two amplifier branches of the beacon set. Heising plate modulation was employed. A photograph of the transmitting set using this method of modulation is shown in Figure 12.

The practical application of this modulation arrangement resulted in a beacon set somewhat more complex than was considered desirable.

Since the maintenance of a "beacon course" or "equisignal zone" in space depends upon a balance of the modulated output of one amplifier branch and its associated loop antenna with the modulated output of the second amplifier train and its loop antenna, it became necessary to insure a balance between (*a*) the r. m. s. values of current in the two antennæ, (*b*) the percentages of modulation in the two amplifier branches, and (*c*) the wave forms of the two modulation frequencies when applied through the Heising chokes. To accomplish this it was necessary to provide controls for varying the radio-frequency voltages supplied from the master oscillator to each amplifier branch, and also for varying the degree of modulation on each amplifier branch. The wave forms of the two modulation frequencies were kept as nearly sinusoidal as possible.

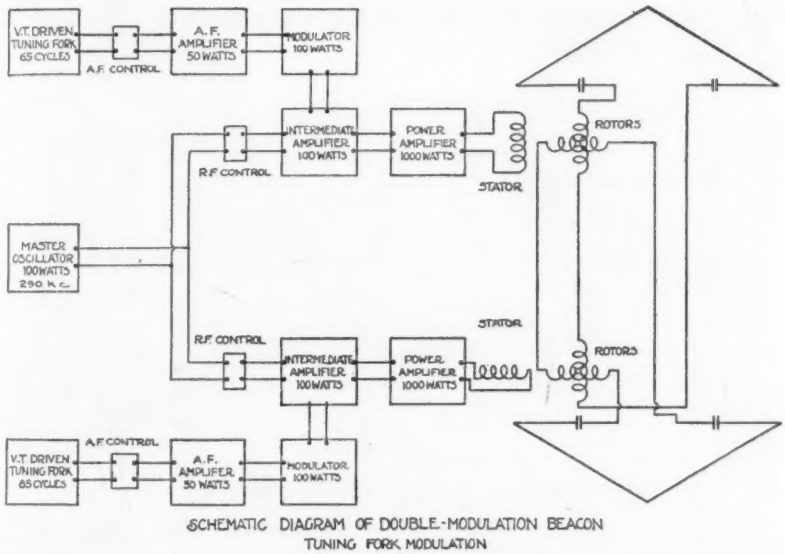

FIGURE 11.—*Schematic diagram of double-modulation beacon using electron-tube driven tuning forks as sources of the modulation frequencies*

It was also important that no coupling exist between the two amplifiers, either by direct induction or by virtue of an impedance common to the two amplifiers. This necessitated the use of a considerable number of expensive condensers and chokes or the adoption of separate generators for supplying the plate and grid voltages to each amplifier branch. The use of the commercial 60-cycle alternating current for heating the tube filaments was also found not possible. Owing to the amount of audio amplification involved, any stray 60-cycle voltages introduced in the early stages were amplified sufficiently to cause a 5-cycle beat on the 65-cycle reed. A further description of this method of modulation is given in (8).

Early in the development of the double-modulation beacon the use of low-frequency generators for supplying the modulation frequencies was attempted. The modulation arrangement was essentially that indicated in Figure 13, where the plates of the intermediate amplifier tubes are supplied through suitable transformers

with high a. c. voltages of the proper frequencies. Synchronous motor drive of these alternators was employed. Owing to the variation of the commercial supply frequency, however, it was found impossible to obtain the desired constancy of speed for driving the low-frequency alternators. However, the considerable simplification of the beacon transmitting circuit network that could be effected by the use of this system of modulation, coupled with the fact that both amplifier branches would then be positively modulated to the same degree, thus eliminating the need for modulation controls, led to further efforts to make its application feasible.

An obvious method of attack was to broaden the resonance curve of the vibrating reeds comprising the course indicator to the point where small variations in the modulation frequencies became unimportant. This could not be carried too far, however, since the reed sensitivity materially decreases as the resonance curve is broadened.

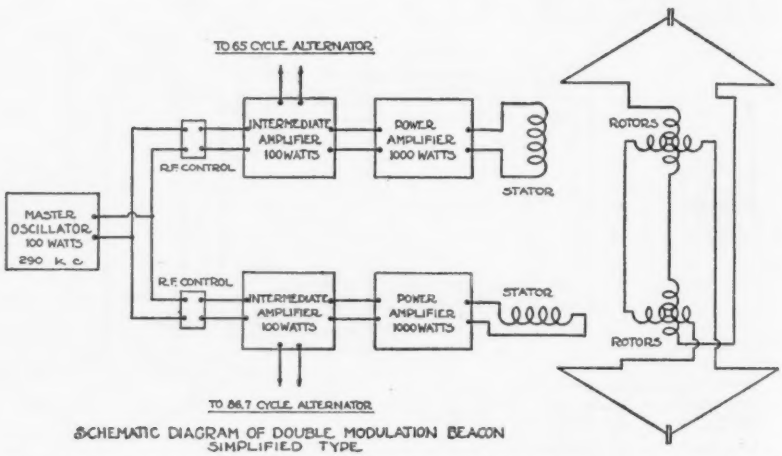

FIGURE 13.—*Schematic diagram of double-modulation beacon using simplified modulation*

A further change in the design of the vibrating reeds made possible a still further reduction in the requirements for speed constancy in the driving motor. The two alternators supplying the modulation frequencies, one having 6 poles and the other 8 poles, were rigidly coupled and driven at 1,300 r. p. m. by the same motor. Variations in the speed of the motor, therefore, resulted in the same percentage change in the two modulation frequencies. The two reeds could then be designed to have, as nearly as possible, equal reductions in deflection for equal percentage frequency change. See reference (10). In many installations this makes possible the use of a synchronous motor as the driving motor. Since the nearest synchronous speed is 1,800 r. p. m., a chain drive is necessary for driving the alternators at 1,300 r. p. m.

By the method described above, variations of the order of 0.3 per cent in the supply frequency can be permitted. Many of the larger power-supply companies maintain their line frequency to this accuracy. Where the frequency variations of the supply mains are greater than this value, a motor other than of the synchronous type

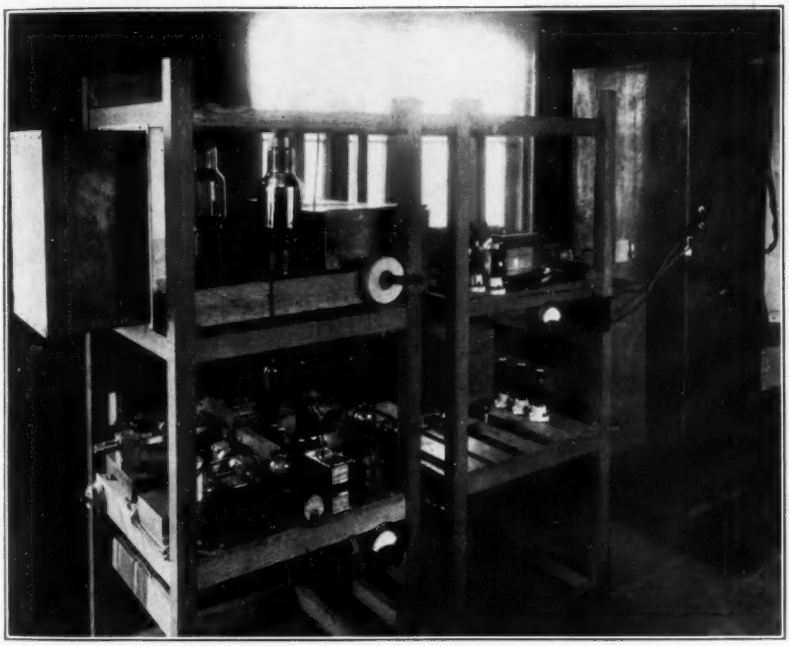

FIGURE 12.—*Transmitting set for double-modulation beacon using tuning fork modulation*

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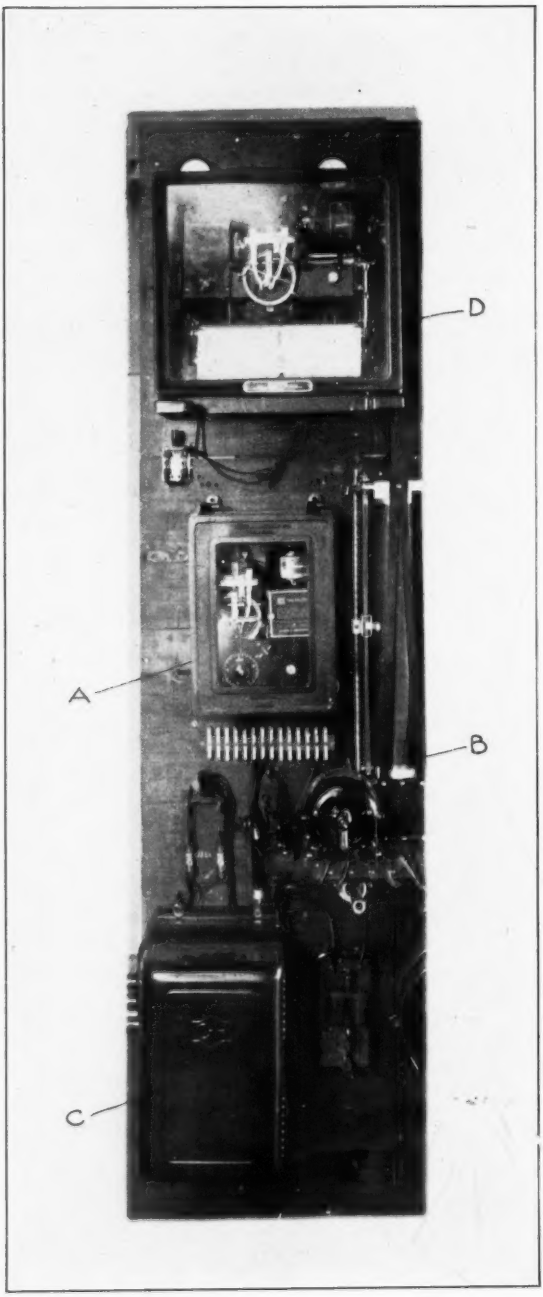

FIGURE 14.—*Control panel for constant frequency unit*

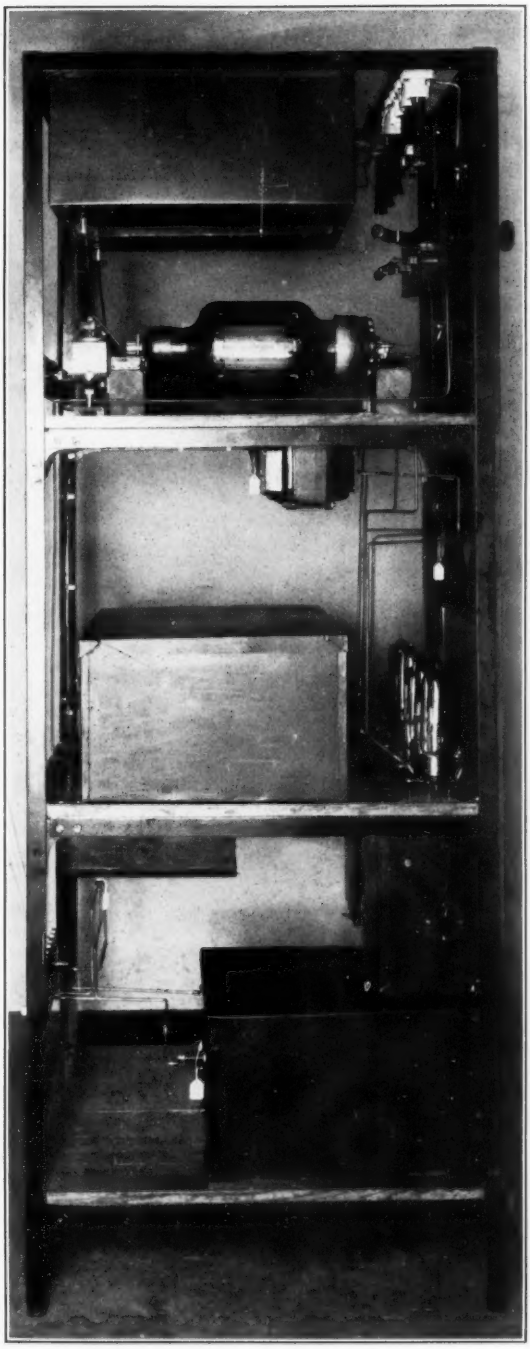

FIGURE 15.—*Transmitting set for double-modulation beacon using simplified modulation*

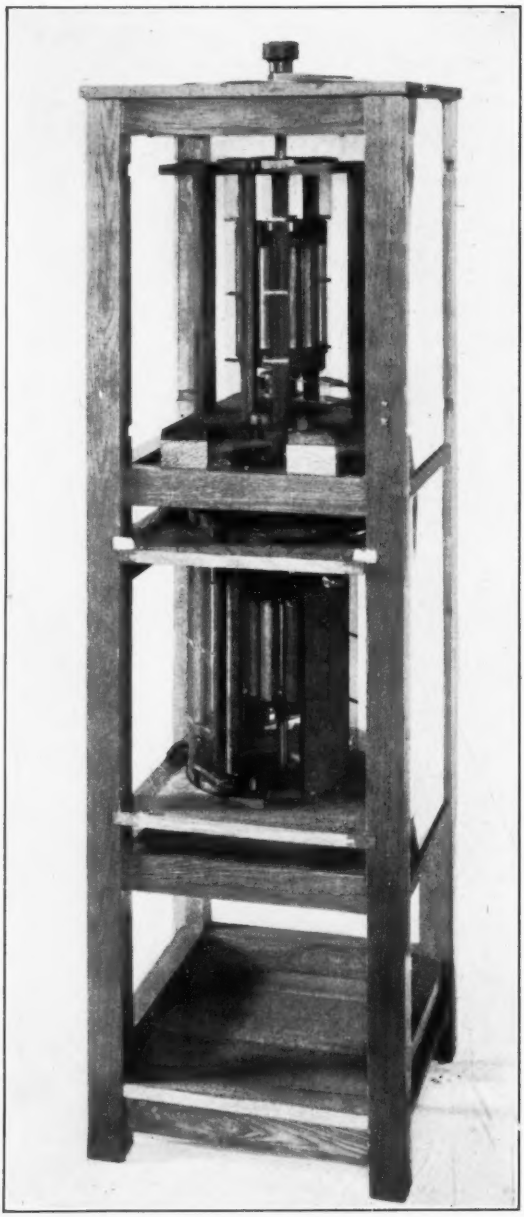

FIGURE 16.—*Double rotor type goniometer used with double-modulation beacon*

must be employed, with provisions for controlling its speed within the desired limit of accuracy. The securing of a suitable constant-speed motor has been difficult. While the advent of television has given considerable impetus to the development of constant-speed motors, most of these are not of sufficient power. A constant-speed unit having the desired characteristics was finally obtained through the cooperation of the Leeds & Northrup Co. and has been in satisfactory operation at College Park for several months. This motor is essentially a rotary converter operated inverted, a portion of the alternating current output being impressed upon a frequency bridge. This bridge operates a galvanometer which controls, through suitable relays, a motor-driven field rheostat connected in the shunt field circuit of the rotary converter. Any change in output frequency of the converter thus results in a change of the speed of the converter in such direction as to correct for the frequency change. A constancy of speed within 0.1 per cent is thus maintained. A photograph of the control panel showing the frequency controller, *A*, the motor-driven field rheostat, *B*, and the automatic starting box, *C*, is shown in Figure 14. A frequency recorder, *D*, used for checking the degree of speed constancy, is also shown. Figure 15 is a photograph of the beacon transmitter using the simplified modulation arrangement. The rotating machinery made necessary when using this modulation is more than compensated for by the great simplification in the transmitting circuit and the attendant improvement in performance and stability. The number of transmitting tubes employed is reduced from 18 to 8.

As noted above, intercoupling between amplifier branches was found to affect the usefulness of the beacon space pattern. To reduce this coupling to a minimum it was found necessary to redesign the goniometer, placing the stator windings in separate compartments in order to facilitate shielding between them. This is indicated in Figure 16. Duplicate rotors, one being placed in each compartment (see figs. 13 and 16), served to make this goniometer the electrical equivalent of the earlier type.

An improvement in the operation of the beacon was obtained by a change in the location of the loop-antenna tuning condensers. Previously the tuning condensers were inserted in the base of the triangular loop antennæ, as shown in Figure 11. The distribution of voltage along the antenna is then as indicated in Figure 17 (a), the portion of the antenna nearest the ground being at the highest potential. With this connection it was found that the tuning of the antennas changed considerably with the weather, often affecting the course settings. The effective capacity to ground constituted the variable factor. By placing the tuning condensers at the apices of the antennas (see fig. 13) the voltage distribution becomes that shown in Figure 17 (b), the portions of the loop antennas nearest the ground being at the lowest potentials. The effect of the weather on the tuning is then very much reduced. The weatherproof box used for housing the tuning condensers on top of the beacon tower may be seen in Figure 2.

4. ADAPTATION OF BEACON TO FOUR INDEPENDENT COURSES

In order to use the beacon practically at any airport, it is necessary to adjust the angles between the equisignal zones arbitrarily so as to make them coincide with the airways converging on the airport.

To understand how this may be done, it is necessary to study the polar pattern of the field radiated by the double-modulation beacon (11).

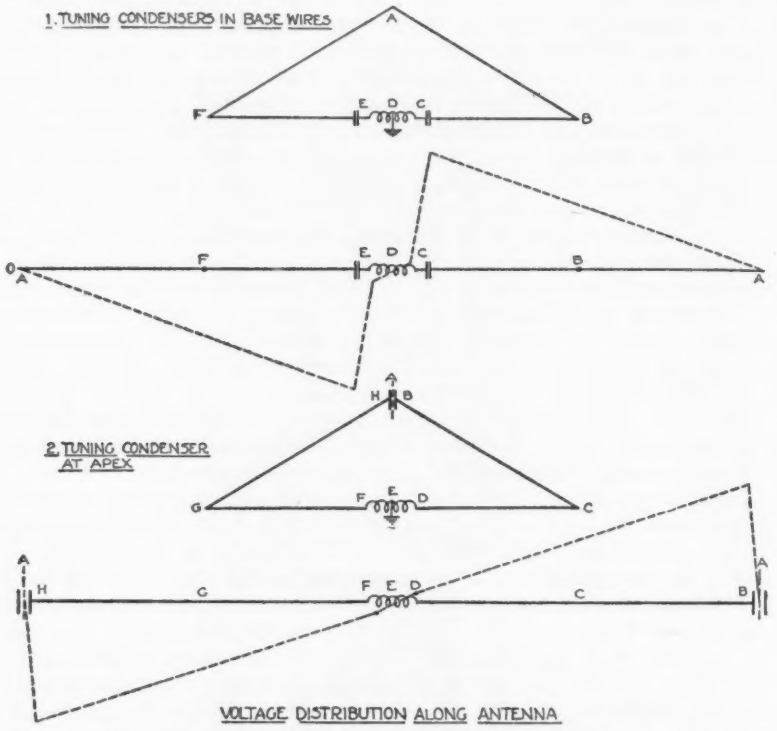

FIGURE 17.—*Voltage distribution along loop antennæ for two different locations of the tuning condensers*

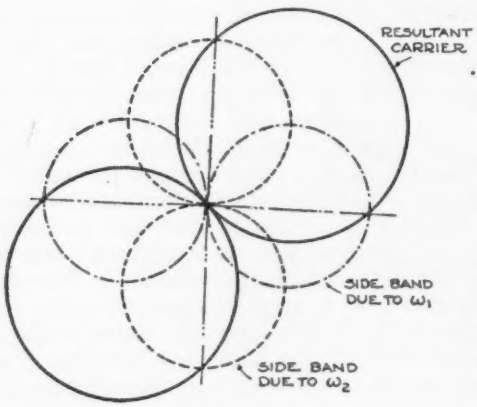

FIGURE 18.—*Space pattern radiated by double-modulation beacon when the carrier currents in the two antennæ are in time phase*

One loop antenna radiates a 290-kc. wave modulated to 65 cycles, while the other loop antenna radiates a 290-kc. wave modulated to 86.7 cycles. The wave due to each antenna may be resolved into a carrier and two side bands. The carriers in the two loop antennæ being of the same frequency and in time phase, combine into a carrier having its maximum intensity along a plane bisecting the angle between the two antennæ. The side bands of the two antennæ do not combine, since they are of different frequencies. The maximum intensity of each side band is therefore in the plane of the antenna radiating it. The space pattern indicating the field intensities of the

combined carrier and the two sets of side bands is shown in Figure 18. Since the reeds operate as a result of the low frequencies in the receiving set output produced by the beating of the side-band frequencies with the carrier in the detector, they respond to a space pattern characteristic as indicated in Figure 19. This assumes a square-law detector. It will be noted that but two courses are produced, practically no signal being radiated in the directions at right angles to these courses.

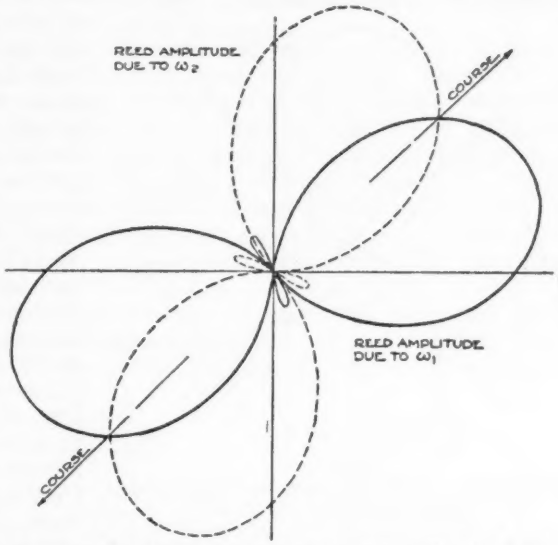

FIGURE 19.—*Received pattern corresponding to space pattern of Figure 18*

In many cases the elimination of the two 90° courses is desirable. In the application of the beacon to course navigation on the airways, however, airports requiring only two courses 180° from each other are the exception rather than the rule. At those airports where two courses are sufficient, these are usually at an angle other than 180°. The beacon may be easily modified to permit the use of four courses at arbitrary angles. By a suitable coupling arrangement to the master oscillator, one of the carrier-frequency currents can be advanced in phase 90° ahead of the other. Since the two loop antennæ are in 90° space phase and their carrier currents in 90° time-phase relationship, a revolving field is set up in space, so that the carrier space pattern becomes circular. (See fig. 20.) The polar pattern as received by the reeds is that indicated in Figure 21, four courses being obtained.

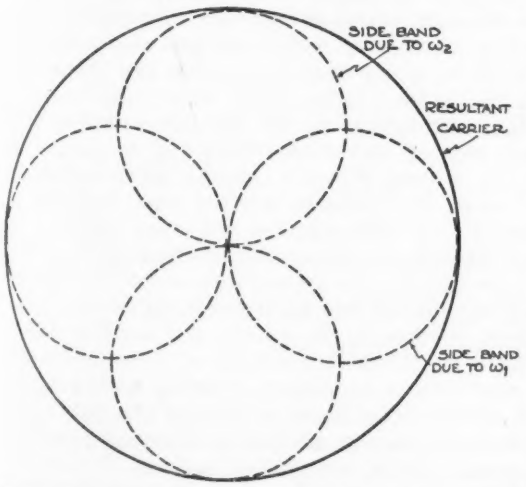

FIGURE 20.—*Space pattern when the carrier currents in the two antennæ are 90° out of time phase*

These four courses may be shifted considerably from their 90° relationship in order to make them coincide with the airways converging on a given airport. Several methods are employed for effecting the course shifting. One consists of reducing the magnitude of current in one of the two loop antennæ. A second method utilizes the circular radiation from a vertical antenna extending along the beacon tower, in addition to the normal figure-of-eight radiation due to each loop antenna. The vertical antenna is coupled to the output circuit of either one or both of the two amplifier branches of the system, the space pattern due to either one or both loop antennæ being thus altered. Combinations of the two methods described are also useful. A detailed description of these methods and an analysis of their degrees of usefulness are given in a separate paper (12).

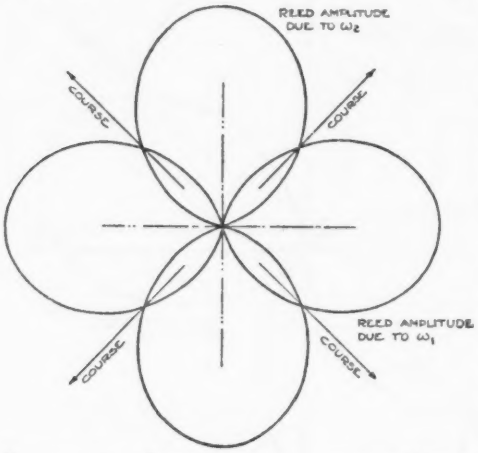

FIGURE 21.—*Received pattern corresponding to space pattern of Figure 20*

5. STATION COURSE-SHIFT INDICATOR

In the practical operation of a radiobeacon system it is necessary to make periodic checks of the correctness of the courses it marks out. For this purpose an indicating instrument was developed and put into operation at College Park, Md., which makes possible the checking of the courses of the 2 or 4 course beacon to within an accuracy of 0.1 of a degree (13). This device indicates at the station whether the courses as laid out in space remain unvarying from day to day. If such variation occurs this instrument shows it, and an adjustment of the transmitting set may then be made to correct this deviation, thus eliminating the necessity of recalibration at a distant point.

The circuit arrangement used in applying this instrument at the beacon station comprises a rotatable pick-up coil inductively coupled, preferably with equal coupling, to the two loop antennæ of the beacon, a detector-amplifier unit, a suitable filter unit, and a differential ratio instrument. The ratio instrument consists of two fixed field coils and an armature or rotor coil. A pointer attached to the rotor coil moves over a suitable scale. The force actions of the two field coils upon the rotor coil are in opposition, so that with equal currents in the field coils the pointer assumes a mid-scale position. The filter unit is so designed that with equal 65 and 86.7 cycle voltages impressed upon the instrument equal currents flow through the field coils. If the 65-cycle voltage becomes greater than the 86.7-cycle voltage, one field coil carries a greater current than the other and the net force acting upon the rotor coil becomes greater than zero, the pointer attached to the rotor coil moving to the left of its mid-scale position. The reverse is true if the 86.7-cycle voltage becomes greater than the

65-cycle. The differential action of the two field coils upon the rotor coil, therefore, serves directly as a means for comparing the relative amount of 65 and 86.7 cycle modulation in the radio-frequency voltages induced in the pick-up coil.

Recalling, now, that the pick-up coil is inductively coupled to the two antennæ of the beacon, rotating this coil about its axis changes the relative coupling to the two antennæ both in magnitude and in sign. Rotating this coil is therefore equivalent to circling the beacon with a nondirectional receiver. There are, then, as many positions of this coil at which the ratio instrument reads zero (that is, equal 65 and 86.7 cycle voltage are induced in the coil) as there are beacon courses. If these coil settings have been determined during the original calibration of the beacon, the correctness of the courses marked out by the beacon may be checked at any later time in very simple fashion. The ordinary course indicator may, of course, be used to replace the differential ratio instrument, together with its filter unit. The accuracy of the course settings will then not be as great (1° to 2° rather than 0.1°).

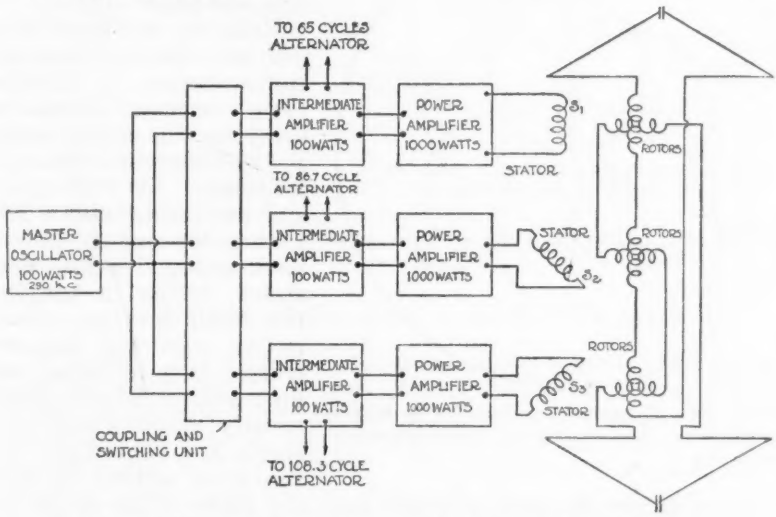

FIGURE 22.—*Schematic diagram of triple-modulation beacon*

IV. THE TRIPLE-MODULATION BEACON SYSTEM

1. TRANSMITTING ARRANGEMENT

To render the beacon system still more flexible and thus make it suitable for use at cities located at the junction of a large number of airways, a beacon transmitter was developed capable of serving 12 courses simultaneously. The increase in apparatus over the beacon described above is not great. The same crossed-coil antenna system and the same circuit arrangements are employed (see fig. 22), except that three amplifier branches, modulated to three different frequencies, are necessary. The modulation frequencies used are 65, 86.7, and 108.3 cycles, respectively. A special goniometer is also required. The rotor system of this goniometer is the same as before; three stator coils are, however, required, one stator coil being

connected to each power-amplifier tube. The stator coils are disposed at 120° to each other, although these angles may be deviated from in order to obtain certain desired conditions.

Since the stator coils are not at right angles to each other, it is essential that but one stator be excited at any given time in order that coupling between stators be avoided. This is accomplished by radio-frequency switching provided in the grid circuits of the intermediate amplifier tubes. By means of a suitable coupling arrangement to the master oscillator the carrier voltages applied to the grid circuits of the three intermediate amplifiers of the transmitter are displaced by 120° in time phase from each other. The modulated voltages applied to the three stator coils are thus similarly displaced. Consequently neglecting the fractions of a cycle when any two of the three voltages are of like sign,[3] but one stator is excited at a time. Further information regarding this method of switching is given in a separate paper (14).

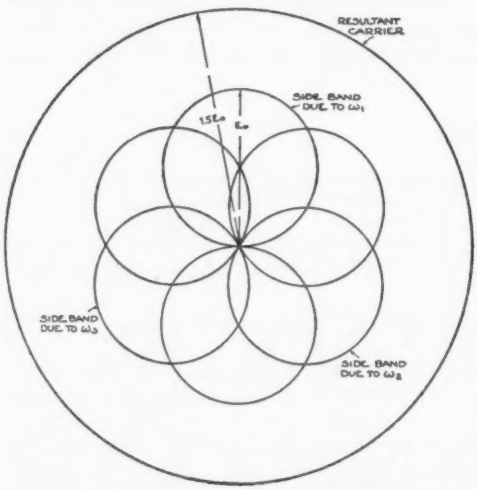

FIGURE 23.—*Space pattern radiated by triple-modulation beacon using radio-frequency switching*

Referring to Figure 22 it will be observed that one stator carries a 290-kilocycle current modulated to 65 cycles, the second stator a 290-kilocycle current modulated to 86.7 cycles, and the third stator a 290-kilocycle current modulated to 108.3 cycles. Each stator, acting in conjunction with the two crossed rotor coils and the two crossed loop antennæ, sets up a system which is electrically equivalent to a single loop antenna. For zero rotor setting the plane of this phantom antenna coincides with the plane of the stator coil considered. Since there are three stator windings, normally disposed at 120° to each other, three such phantom antennæ (also crossed at 120°) exist, each phantom antenna carrying current of the same radio-frequency, but modulated to a different low frequency. The space pattern radiated by the beacon is given in Figure 23. The carriers in the three phantom antennæ being 120° out of phase both in time and in space, a revolving field is set up, the resultant carrier space pattern being represented as a circle. The three sets of side bands are of different frequencies and do not combine. Assuming square-law detection, the polar pattern as received on the reeds is given in Figure 24. This pattern is obtained by the beating of each side band with the in-phase components of the three carriers making up the resultant revolving field. (See (14).)

[3] This assumption is permissible, since the power transmitted during these fractions of a cycle is small.

As will be observed from Figure 24, 12 useful courses exist, any two adjacent courses being separated by 30°. Of the 12 courses, 4 courses (*M*, *N*, *O*, *P*) can be received by a reed box tuned to 65 and 86.7 cycles, 4 courses (*Q*, *R*, *S*, and *T*) by a reed indicator tuned to 86.7 and 108.3 cycles, and 4 courses (*W*, *X*, *Y*, and *Z*) by an indicator tuned to 65 and 108.3 cycles. The equisignal zone of 2 of each set of 4 courses (for example, *M* and *N*) is from 1° to 1.5° wide, while the equisignal zone for the other two courses (viz, *O* and *P*) is from 2° to 3° wide.

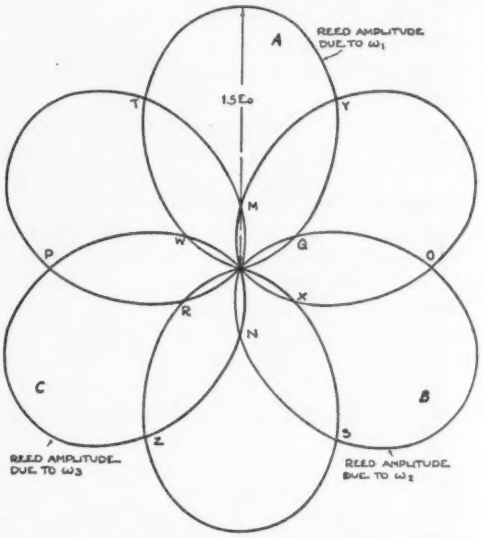

FIGURE 24.—*Received pattern corresponding to space pattern of Figure 23*

A 12-course radio range of the type described has been installed at College Park, Md., and is giving satisfactory results. On the basis of the results obtained, the Airways Division of the Department of Commerce is constructing seven sets of this type with a view to perfecting the design and employing these sets on suitable air-mail routes.

2. SPECIAL THREE-REED COURSE INDICATOR

To obviate the necessity for using three separate indicators in order to receive all 12 beacon courses, a special course indicator containing 3 reeds tuned to the 3 modulation frequencies of the beacon has been developed. Using this indicator, any 1 of the 12 beacon courses may be followed. Two shutters are employed on the indicator front. One shutter serves to expose any 1 of the 3 sets of reed combinations which go to make up the 12 course indications, each reed combination (for example, the two reeds tuned to 65 and 86. 7 cycles, respectively) serving 2 sets of 2 courses (viz, *M*, *N*, and *O*, *P* of fig. 24). Two different colors are exposed corresponding to each setting of this shutter in order to facilitate the choice of the proper 2 reeds for a given course. Thus, if on the airways map, courses *M* and *N* are shown in black and courses *O* and *P* in red, the shutter setting which exposes the 2 reeds tuned to 65 and 86.7 cycles, respectively, also exposes the 2 colors black and red. The second shutter provided on the indicator front serves the same purpose as the shutter used with the 4-course indicator (see Sec. III, 2); that is, to simplify the choice of the proper relative position of the two reeds in use in order that the rule (longest reed shows side off course, turn to the shorter reed) may apply. This shutter has two settings, one exposing the words $\left[\begin{matrix}\text{TO}\\ \text{FROM}\end{matrix}\right]$ and the three colors corresponding to

the three sets of courses (*M*, *N*), (*Q*, *R*), and (*W*, *X*) (see fig. 24), while the other setting exposes the words [FROM / OL] and the colors corresponding to the three sets of courses (*O*, *P*), (*S*, *T*), and (*Y*, *Z*). The pilot uses the 12-course indicator exactly as he would the 4-course indicator, except that he must set 2 shutters to expose the color (according to the airways map) of the course to be flown rather than one.

A photograph of this special 3-reed indicator mounted on the intrument board of an airplane is shown in Figure 25. The indicator is of cylindrical shape in order to conform with the other airplane instruments. The operating characteristics of this indicator are the same as for the 2-reed type, with the exception that since three pairs of actuating coils are employed, 50 per cent greater voltage is required for equivalent reed deflections. The sensitivity may be made equal to that of the 2-reed type by means of a suitable arrangement for switching out the pair of coils controlling the reed not in use. This special indicator is further described in (10).

3. ADJUSTING THE COURSES TO AIRWAYS AT ARBITRARY ANGLES

With the 12-course radio range, as with the 4-course type, the problem of adjusting the angles between the beacon courses arbitrarily so as to make them coincide with the airways converging on a given airport must be solved. The methods previously described (see Sec. III, 4) for effecting the arbitrary shifting of the courses of the 4-course beacon from their normal positions are all applicable to the 12-course system. The first method described is the simplest and may well be employed. The other methods, although entirely practicable, are not quite as simple and need not be used, particularly since an additional method, applicable only to the 12-course beacon and very simple, is available.

This method consists of displacing the stator windings from their 120° space relationship, thereby modifying the space pattern radiated by the beacon. It will be recalled that for zero rotor setting the plane of each phantom antenna coincides with the plane of the stator winding which produces it. A displacement of a given stator winding, therefore, results in a displacement of the space characteristic due to the phantom antenna associated with that stator winding. The space characteristics of the three phantom antennas may, therefore, be crossed at any angles found desirable. This does not mean, however, that in the received polar diagram (see fig. 24) the three component characteristics (*A*, *B*, and *C*) are necessarily crossed at the same angles. As stated previously, each set of side bands beats with the in-phase component of the carrier due to each phantom antenna, yielding the received polar pattern corresponding to that side band. When the three sets of side bands (and consequently the three carriers) are symmetrically disposed in space, there is reason to expect a symmetrical received pattern. With an unsymmetrical radiated space pattern, however, the received pattern is not necessarily similar to the radiated pattern. Nevertheless, the three component characteristics of the received pattern are displaced from their 120° relationship, the angles between adjacent beacon courses being, therefore, adjustable.

FIGURE 25.—*Special 3-reed course indicator mounted on airplane instrument board*

FIGURE 26.—*Airplane showing vertical pole antenna*

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Using the two simple methods outlined it becomes possible to adjust the angles between the beacon courses over a wide range of values. (See (14).) Obviously, each installation will require a different adjustment, which may be more or less difficult. The statement that these methods will prove successful in all possible cases can not therefore be made.

4. INDICATION OF CORRECTNESS OF COURSES

The course-shift indicator described for use in checking the correctness of the courses marked out by the 4-course beacon is not applicable for use with the 12-course system. If the circuits of the filter unit could be made sufficiently sharp to exclude the third modulation frequency (108.3 cycles), this device could be used for checking 4 of the 12 courses. It is difficult to obtain the necessary sharpness of tuning. The special 12-course indicator is therefore used to replace the differential ratio instrument and filter unit, thus making possible the checking of all 12 courses to within 1° to 2°.

V. AIRPLANE RECEIVING EQUIPMENT

1. AIRPLANE RECEIVING SETS

The beacon system can be used with any receiving set which operates at the frequencies employed merely replacing the telephone receivers by the simple reed-indicator unit. There are, however, a number of special conditions involved in receiving on an airplane, and the bureau has developed special receiving sets (15) in order to use the beacon system under the most advantageous conditions.

The receiving set designed employs 6 tubes and weighs less than 15 pounds, the auxiliary batteries weighing an additional 10 pounds. The receiving set operates in the frequency range from 285 to 350 kc. and is used to receive either the beacon signals or radiotelephone weather messages at will. It is highly selective and sensitive. The audio-frequency amplifier is specially designed to be efficient at the low-modulation frequencies used in the beacon. The selectivity of the set is supplemented by the selectivity of the vibrating reeds, which helps greatly in reducing interference. Nevertheless, it is important that a good degree of selectivity be provided in order to make the most efficient use of the frequency channels provided for this service, and also to make the receiving set suitable for the reception of weather telephone messages. The set has remote-control arrangements for tuning and volume, so that it may be mounted in any location on the airplane.

The bureau interested several manufacturing companies in building receiving sets of suitable characteristics. Three companies are now ready to furnish receiving sets, all of which have proved satisfactory.

The result of more than two years of flying on the visual-type radio range has proved that a receiving set designed for beacon reception should have as high an undistorted power output as possible. Since the reeds are practically immune to interference, atmospheric and other disturbances will not affect their operation unless they are of sufficient strength to overload the receiving set. The greater the overload point of the receiving set the greater will be the range of the beacon during severe interference.

The incorporation of an automatic volume control is highly desirable, since such a device would still further reduce the effort expended by a pilot in making use of the radio navigational aids. The 2-course, the 4-course, and the 12-course visual radio ranges as now employed will each function properly with or without automatic volume control. Automatic volume control is, however, not possible with the aural radio range, since its effect would be to reduce to equal signal strength the two coded signals the relative magnitudes of which it is desired to compare. The chief value of automatic volume control with the visual radio range would be within 10 to 15 miles of the beacon in the region where the beacon signal strength changes most rapidly. At great distances from the beacon an auxiliary manual control would be essential, since the effect of large interfering signals (when using automatic control) would be to reduce the amplitude of vibration of both reeds. This may well prove troublesome, particularly since interference is normally intermittent in nature.

2. AIRPLANE ANTENNA

The development of receiving sets having the necessary sensitivity made possible the use of an antenna system on the airplane, consisting of a metal pole extending vertically from the fuselage, the total length of this pole being but 6 to 8 feet. (See fig. 26.)

The antenna system in common use on airplanes previous to this development was the weighted trailing wire. This system had numerous disadvantages. It was heavy, difficult to handle, and dangerous. It had marked directive properties, resulting in erroneous indications of the beacon course unless it lay in the vertical plane containing the transmitting station (16); in additional errors when near the beacon (where the angle between transmission path and ground is appreciable); and in marked apparent variations of the beacon courses at night.

The existence of errors at night in the apparent direction of radio stations has long been known (17, 18). Investigations as to the causes of direction shifts have been under way for some time (19), and experimental proof has been secured that these shifts are largely due to the horizontal component of the downcoming reflected or refracted wave. The existence of these apparent shifts in the directive radiobeacon courses was first observed in August, 1927 (20). The tests were made on the aural type beacon using a trailing-wire antenna for receiving on the airplane. The results of these tests are summarized below.

1. Within 25 miles of the beacon the shifting was not of a very serious nature.
2. At 50 miles the shifting became pronounced, but due to the zone appearing to be stationary in its proper position for possibly 75 per cent of the time, the beacon could still be depended upon when used with judgment.
3. At a distance of 100 miles the shifting became very pronounced and persisted for more than 50 per cent of the time, giving the beacon a questionable value.
4. At 125 miles the beacon was of no further use as a guide.

Later tests made on the ground, and also reported in reference (20), indicated that the use of a vertical antenna reduced to a considerable

degree the amount of variation of the course. This was one of the contributing reasons which led to the adoption of the vertical pole antenna. Since this type of antenna is not affected by horizontal electric fields, the results obtained were in accordance with what was expected.

More recent tests carried on periodically during the past two years, using the visual type beacon, tend to corroborate these results. With tuned-reed indication it became possible to estimate more closely the variation of the courses in degrees. The tests were made in the air and on the ground, the results obtained in each case being very nearly the same. These results are summarized below.

1. Within 75 miles of the beacon the shifting was not serious.
2. At a distance of 125 miles the shifting was readily detectable, maximum variations ranging from 10° to 20° being observed. The period of the variations appeared regular, the reed indicator showing "off course" first to one side and then to the other. However, the true course could still be estimated with a fair degree of accuracy, visual indication having the psychological effect of averaging out the variations.
3. At a distance of 200 miles the course shifting appeared not very much worse than at 125 miles, an estimation of the true course being still possible. Not enough data was taken at this distance to permit of definite conclusions.

The improvement due to the use of the vertical antenna is evident. The normal range expected from the beacons is about 125 miles. For this range the apparent night variations of the course should not prove serious.

An added advantage for the use of the vertical pole antenna is that it becomes possible to guide an airplane directly over the beacon tower. With the trailing wire this was a difficult feat, becoming impossible when a side wind produced a side slant to the antenna. Furthermore, since the vertical antenna is affected only by vertical electric fields, a region of zero signal is met with directly above the beacon tower, where no vertical field exists. The beacon can thus be located to within 100 to 200 feet when the airplane is not over 1,000 feet above it, a most valuable aid in fog.

3. ENGINE IGNITION SHIELDING

The use of a sensitive receiving set, together with a short vertical antenna located near the airplane engine ignition system, makes necessary a considerably more rigorous shielding of the ignition system than was previously required to prevent ignition interference. The entire electrical system of the ignition must be encased in a high-conductivity metallic shield. This requires that the magnetos be provided with such metal covers as will completely inclose the distributing heads. The booster-magneto outlet must also be covered. All distributing wires must be inclosed in a metal tube or braid, the spark plugs must be completely shielded and the booster leads and leads to the ignition switch, including the ignition switch itself, similarly treated.

The bureau has been in active cooperation with airplane engine, magneto, spark plug, and cable manufacturers in an effort to develop a safe method for effecting this shielding and to make the necessary

equipment available commercially. As a result of this cooperation, suitable shielding assemblies may now be purchased for use on all Wright and Pratt-Whitney airplane engines. A metallic ignition manifold is employed with high-tension cable drawn through it in the usual way. The leads from the manifold to the spark plugs and the groups of leads from the manifold to the magneto outlets are inclosed in liquid-proof flexible aluminum tubing with copper braid on the outside to insure effective shielding. Each flexible tube is suitably fitted to the ignition manifold and to the magnetos or spark plugs, as the case may be. The magnetos are provided with covers which completely inclose the distributor blocks. A single outlet permits the use of an elbow fitting for connection to the large flexible metal tubing. This elbow fitting differs for different types of engines. Outlets are provided in the elbows for the booster and ground leads. The spark plugs are of a type in which the shield is an integral part and are provided with elbows for connection to the smaller flexible metal tubing. The ignition switch is totally inclosed in a metal cover, the booster magneto is also covered, and the leads from the magnetos to the ignition switch and booster magneto are inclosed in flexible metal tubing. The complete assembly insures electrical safety, mechanical sturdiness, liquid proofing of magnetos, spark plugs, and ignition cable, and ease of installation and of servicing.

At a conference held at the Bureau of Standards on June 11, 1929, in response to a number of requests from representatives of the aircraft and radio industries, the present status of shielding was discussed. In addition, a beginning toward the standardization of shielding-assembly practice was made and a series of standard tests whereby the mechanical, electrical, and radio efficiency of a given shielding installation may be determined were adopted.

Further details regarding the bureau's work in this field are given in a separate paper (21).

VI. MARKER BEACONS

The directive radiobeacon will successfully guide a pilot along a given course, but does not directly indicate his exact location along that course. Where it is desirable that this indication be given (for example, at the intersection of two beacon courses or at a dangerous portion of the airway), it can be obtained by the installation of a small marker-beacon transmitter of very low power (a few watts). The marker beacons operate on the same radio-frequency as the main beacon. This signal operates a 40-cycle reed indicator mounted at a suitable location on the airplane instrument board and connected in series with the main course indicator, and is received for two or three minutes as the airplane passes over the marker. The pilot can thus locate his exact position on the airway.

The first experimental work with the marker beacon involved the use of a reed indicator tuned to 60 cycles. Modulation of the marker beacon was accomplished by supplying the oscillator with a plate voltage secured from the commercial 60-cycle supply. This resulted in an inexpensive marker-beacon transmitter. The use of 60 cycles was not practicable, however, since a 5-cycle flutter was observed on the 65-cycle reed of the main course indicator during the entire period that the receiver was within the range of the marker-beacon

transmitter. This destroyed the usefulness of the main beacon course during that period. A self-rectifying circuit, still using the 60-cycle supply but giving a 120-cycle modulation frequency, was then tried, the marker-beacon reed being tuned to 120 cycles. The 5-cycle flutter on the 65-cycle reed still occurred. The frequency of 40 cycles was then chosen. The beat frequency (25 cycles) is then sufficiently high so that neither reed has opportunity to follow this beat frequency owing to mechanical inertia. A 4-pole alternator driven by a 6-pole synchronous motor operated from the commercial supply is used as the 40-cycle source.

In the earlier experiments it was decided to use an open antenna with the marker beacon and to code the transmitted signal with a characteristic corresponding to that used on the light beacon at the same location (if there is one there). The use of an open antenna is, however, not entirely satisfactory. A sharp indication of the exact marker-beacon location is obtained only when passing directly over the antenna, a region of zero signal being then observed. The use

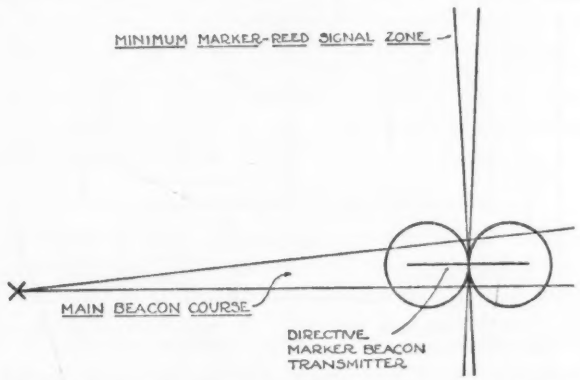

FIGURE 27.—*Diagram illustrating use of directive marker beacon on the airways*

of a loop antenna, oriented as shown in Figure 27, removes this objection. As will be observed from the loop characteristic, sharp indication of a line perpendicular to the airway route is obtained, a drop in the marker-beacon reed indicator deflection being observed when crossing this line. Coding of the transmitted signal is, however, not practicable when using this antenna arrangement. Actual use on the airways will determine which antenna system is the more desirable.

When located at the intersection of two main beacon courses, an arrangement must be provided on the marker beacon to permit the emission of its signal on each of the two radio-frequencies used by the main beacons. A satisfactory audio-frequency switching arrangement for accomplishing this purpose has been developed and is included in the circuit diagram of Figure 28. Either open or loop antennæ may be employed. The two antennæ shown are tuned to the two different beacon frequencies. These are excited alternately at a 40-cycle rate by means of transformer *G*.

VII. FOG LANDING

By the use of the radiobeacon system described, it will become entirely feasible to fly between any two points along a given airway and to arrive within a few thousand feet of the desired destination regardless of weather conditions. The problem of effecting a safe landing during fog and extremely low visibility is not yet, however, completely solved.

Recent tests indicate that fog-penetrating lights are not yet available. The dissipation of fog by mechanical means has been the subject of considerable laboratory experimentation, the general result being that it is not economically possible on a useful scale.

The most feasible method of attack at the present time appears to be in the application of radio. When attacked from this angle, the problem of fog landing resolves itself into two separate problems, namely, field localizing and the development of a suitable altimeter.

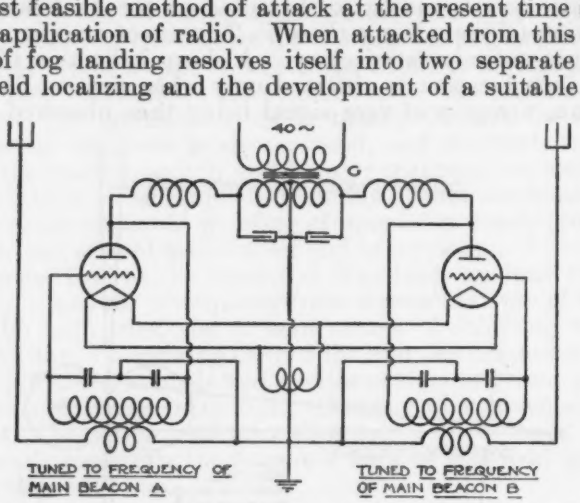

FIGURE 28.—*Circuit diagram of marker beacon located at the intersection of two main beacon courses*

1. FIELD LOCALIZERS

Practically all previous experimentation in this field has been in the use of "leader cables." The principal installations are those of the British Government at Farnborough and of the French Government at Chartres. The British installation uses a complete circuit around the landing field with a visual indicator on the airplane instrument board. The French installation uses straight cables. The Loth Co., of Paris, has also conducted experimental work using straight cables.

The ground equipment at Farnborough consists of an oval loop of cable about 5 by 2 miles buried 2 feet in the ground. One of the straight sides of this oval loop passes through the airdrome. Near this straight side and surrounding the portion of the airdrome free from obstructions is a second smaller oval loop. A pilot circles around the major loop coming lower and lower. Once each revolution he receives a signal from the smaller loop indicating that he is directly over the airdrome. When he is at a sufficiently low altitude and over the airdrome a safe landing may be effected. An obvious disadvantage of the leader cable method of field localizing is its great cost.

The success obtained with the radio range in its application to point-to-point flying suggests its possibilities as a field localizer. With the main beacon used for guiding an airplane to a given landing field, a low-power beacon with small loop antennæ may be employed for marking out the major, or most desirable axis or runway of the landing field. This can be done quite as effectively as with leader cables. For example, consider a class A field having the required dimensions of 2,500 by 2,500 feet with two perpendicular runways at least 300 feet wide. The equisignal zone of the two-course radiobeacon is at a maximum 5° wide. (The use of the 2-course beacon is here assumed because of the obvious advantages of eliminating the 90° courses.) If, then, a course is oriented along a particular runway, with the beacon at one end of the field, a pilot can locate the axis of this runway at the other end of the field within 100 feet. He is thus certain to land on the runway.

An installation has been made at College Park, Md., and a second installation for the Guggenheim Fund for the Promotion of Aeronautics at Mitchel Field, Long Island, with a view to obtaining a practical arrangement. Each installation includes a localizing beacon for guiding an airplane along the major runway of the field and suitably placed marker beacons for defining the beginning of the hazard-free approach to the field and the limits of the field. This arrangement, combined with a suitable landing altimeter, gives promise of making fog landing feasible.

3. LANDING ALTIMETERS

The method of fog landing demonstrated by Lieut. J. H. Doolittle, of the Guggenheim fund (33), consists of maneuvering the airplane into a glide from a position in space of fixed bearing and altitude with respect to the landing field. The barometric altimeter is adjusted to read altitude above the field based on data communicated from the ground. If the landing is entirely blind, the glide continues until a landing is made without the usual "flattening-out," owing to the lack of knowledge of the altitude to the accuracy required.

Experiments are being undertaken by a number of investigators looking toward the development by several means of altimeters indicating the absolute height above ground. One is the developments of a sonic altimeter. Another device is the capacity altimeter which measures the distance from the ground by detecting the change in the electrical capacity between two plates on an airplane, as the airplane approaches the ground. A third method is by the use of direct reflection with radio waves. It is doubtful at the present time whether any of these instruments will be sufficiently sensitive for use in "flattening-out" so as to make a normal landing. These instruments when available will, however, be exceedingly valuable in determining the altitude from which the glide shall be started in landing and also in maintaining a safe altitude during point-to-point blind flying.

The bureau is conducting experiments on making possible normal three-point landings in dense fog. A special radio beam at the landing field is so oriented in space as to define the proper gliding path which if followed will permit such landings. Experiments on the production of such a beam with a suitable visual indicating device on the airplane show some measure of success. High frequencies are

employed (about 70 megacycles), making the necessary equipment on the ground and on the airplane rather simple. This arrangement, if found suitable, will, of course, merely obviate the need for an altimeter in landing; the localizing and marker beacons will still be necessary.

VIII. TESTS OF THE BEACON SYSTEM

The practicability of the visual radio range system described has been demonstrated by a considerable amount of test flying on the College Park station. The useful distance range of the beacon under summer and winter conditions is a function of the power used at the beacon station, the length of receiving antenna, sensitivity and overload point of receiving set, sensitivity of the reed indicator, and degree of airplane-engine ignition shielding.

Using 1 kw. tubes in each power-amplifier stage of the beacon transmitter, a current of 12 amperes may be obtained in each loop antenna. The antennæ are triangular in shape with a base 300 feet long and a net height of 70 feet. On the airplane a receiving antenna 6 to 8 feet long was employed. The receiving set with which 90 per cent of the tests were made has a sensitivity of about 120 decibels and begins to overload slightly at an output voltage of 12 volts. Serious overloading occurs when the output voltage is 20 volts. The 4-course reed indicator has an impedance of about 4,000 ohms and requires 4 volts across its terminals to give normal reed deflection; the 12-course reed indicator has an impedance of about 6,000 ohms and requires 6 volts. Perfect ignition shielding is assumed. Under these conditions, the average winter range of the 4-course beacon is 200 miles and the average summer range about 100 miles. With the 12-course beacon the useful distance depends upon the courses used. Referring to Figure 24, the range on courses *M*, *N*, *Q*, *R*, *W*, and *X* is 150 miles in the winter and 75 to 90 miles in the summer, respectively. The range on courses *O*, *P*, *S*, *T*, *Y*, and *Z* is as great as with the 4-course beacon. The reduction of indicator sensitivity as compared with the 4-course type is compensated for in part by the fact that in the 12-course beacon 3-power amplifier tubes rather than two feed power into the antennæ. In addition, the greater indicator impedance more nearly matches the plate impedance of the output tube of the receiving set.

Preliminary tests using a receiving set of approximately the same sensitivity as the receiving set mentioned above but having an overload voltage of about 30 volts show that the summer range may be somewhat increased over the figures given above. A typical test will be described. Using the first receiving set on a partially shielded airplane, a range of 40 miles was obtained before the ignition interference began to affect the operation of the reeds. With the second receiving set, having the greater overload point, mounted on a different airplane (but shielded to approximately the same degree), the College Park beacon signals were received at Hadley Field, N. J., a distance of about 185 miles, the reeds operating properly and with full-scale deflection. Although the conditions under which the tests were taken were not identical, the effect of greater load capacity in the receiving set is nevertheless positive.

The remarkable selectivity of the reed indicator has been demonstrated in numerous flights from College Park, Md., to Hadley Field, N. J., with the double-modulation radio range at College Park and the aural-type Hadley beacon both operating on the same radio-frequency and approximately the same power. Using the receiving set having the lower overload voltage rating, the interference due to the Hadley beacon began to affect the reeds at a point about 140 miles from College Park and only 45 miles from Hadley.

The ruggedness of the radio equipment on board the airplane was demonstrated when an airplane crashed in July, 1929. Several pilots remarked that this was the worst wreck that this particular type of airplane had ever experienced. All the instruments on the instrument board except the reed indicator were completely demolished. The shock mounting case for the reed indicator was seriously damaged. The indicator itself, however, was found to be in good condition and in accurate adjustment. The receiving set, which was shock-mounted in a compartment behind the pilot's cockpit, also escaped with minor injuries.

The simplicity of operation of this system and its adaptation to the needs of the pilot is evidenced by the following typical test: On a day of low visibility a pilot, unfamiliar with the route, took the air in Philadelphia for Washington with no maps or instructions as to landmarks; he was told to proceed to Washington (a distance of 120 miles) and land at College Park Field solely in accordance with the guidance given by the beacon indicator on his instrument board. He not only flew in a straight line to Washington, but when over College Park Field, the location of which he did not know, the sudden drop in the reed deflections told him he was at his journey's end, whereupon he landed.

IX. COMPARISON OF VARIOUS TYPES OF RADIO AIDS TO AIR NAVIGATION

It is of interest to compare the advantages of the radiobeacon system described in this paper with the other systems in use for guiding aircraft. A brief description of the various systems employed is given in the introduction to this paper under "Previous work." The discussion will be limited to the application of these systems to course navigation on fixed airways which is of primary importance in the United States.

1. REQUIREMENTS FOR COURSE NAVIGATION ON FIXED AIRWAYS

The fundamental requirement of a radio system for guiding airplanes traveling the fixed airways is that it shall give the pilot information to enable him to continue along a given airway when no landmarks or sky are visible. If he leaves the course, it should tell him how far off he is and to which side, should show him the way back to the course, and should inform him when he arrives at his destination. Guidance along the airway means guidance along the route regularly flown, with its emergency fields, lights, and other facilities. The guidance system must be entirely free from errors owing to wind drift. The system must provide service to all airplanes flying the course and must be adaptable to the complex conditions on the busiest airways.

In addition to these requirements, there are a number of additional desiderata which are not strict necessities. The identity of the portion of the airway traversed should be indicated by the radio signals utilized. The service should be continuous rather than intermittent. The pilot should receive the service by a mere glance at an instrument, being free from any necessity of using ear phones, or adjusting anything, or correlating with other instruments, or changing the course of the airplane. The radio-frequencies, power, type of emission, and location of transmitting stations should be so chosen as to serve the needs with maximum efficiency and conservation of the limited radio channels. The radio equipment on the airplane should be simple, rugged, and inexpensive. Finally, the transmitting equipment on the ground should be as simple as possible.

2. DIRECTION FINDER ON AIRPLANE

The use of a direction finder on aircraft makes possible a very simple transmitting station on the ground. Available radio stations may be utilized and guidance obtained in every desired direction. Simultaneous service to any number of airplanes is possible. Complicated equipment must, however, be carried aboard the airplane. This system does not fulfill the major requirements listed above. It does not take care of wind drift, resulting in circuitous courses to the airport. It therefore does not generally guide aircraft over the lighted or marked airway and does not give a pilot the advantage of the emergency landing fields and other aids along the airways.

3. DIRECTION FINDER ON THE GROUND

This system also has the advantage of giving guidance in every desired direction. The apparatus on the ground is more complicated than with the previous method, two or more radio stations with an intercommunication system being required in order to give the pilot a bearing. Simultaneous service to several airplanes in the air is not possible, individual service to each airplane from two stations being necessary. The apparatus on the airplane is bulky, comprising a transmitter and a receiver. Two-way communication must be maintained. Since but infrequent bearings are available, the pilot must rely on blind flying by means of his other flight instruments during the greater portion of his flight. Consequently, the route traveled is not generally over the regular airways.

4. ROTATING RADIOBEACON

This system has relatively simple apparatus both on the ground and aboard the airplane. The use of this system, however, burdens the pilot more than is desirable. It is capable of giving simultaneous service to any number of airplanes in any direction. This service is, however, intermittent and slow, requiring at least 30 seconds for each bearing. Drift may be checked by determining positions periodically and correction may be applied. Since the determination of a minimum signal must be made, this system is particularly subject to interference and atmospheric disturbances. The errors in course determination with this system are somewhat greater than with the directive-type radiobeacon.

5. FOUR-COURSE AURAL RADIO RANGE

The use of a directional transmitter places the complicated apparatus on the ground under skilled supervision and makes possible the use of a simple receiver on the airplane for taking advantage of all radio aids. The radio-marked channels coincide with the airways so that the pilot can utilize the other navigational aids provided on these airways. The system can furnish simultaneous service to any number of airplanes. Wind drift is readily detected. An observation is made without any necessity for maneuvering the airplane or correlation with maps or any flight instrument. The safest route is radio marked, and is over the route flown in good weather. This aids greatly in missing obstructions and safely takes the pilot through mountain passes and canyons. The system acts as a homing device, guiding the pilot to the airport and informing him when he has reached the airport. It has the disadvantages of requiring the pilot to wear head phones and to recognize coded signals. It is at present capable of serving but four courses and can not, therefore, furnish guidance in more than four directions.

6. FOUR-COURSE VISUAL RADIO RANGE

This system has all the advantages of the 4-course aural system. In addition, visual indication removes the necessity of wearing head phones. A glance at the reed indicator tells the pilot his exact position with respect to the course. No skill is required on the part of the pilot in the use of this system. Finally, the selectivity of the reed indicator renders the system almost immune to interference from other services or atmospheric disturbances. Course guidance is therefore available when no other radio service is possible. The chief disadvantage of this system is that only four channels are available, thereby making its use difficult at airports located at the junction of a large number of airways.

7. MULTICOURSE VISUAL RADIO RANGE

This system removes the only objection inherent in the one just described. Twelve radio channels (with the angle between adjacent channels controllable over a considerable range) are sufficient for the busiest airport. Directional guidance is obtained in any desired direction with all the advantages of the previous system.

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